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Testing of Indoor Radon Reduction Techniques in Central Ohio Houses: Phase 1 (Winter 1987-1988)

Acres International Corp., Amherst, NY

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16. ABSTRACT The report gives results of tests of developmental radon reduction techniques installed in 16 houses near Dayton, Ohio. Sub-slab suction and sump (drain tile) suction reduced radon levels in five basement houses below 4 pCi/L, based on short-term measurements. In one of the houses, soil gas flow in the system was only 2 L/sec. In two houses with basements plus adjoining slabs on grade, sub-slab suction in the basement alone adequately reduced radon levels in the entire house. Radon was reduced by over 90% in each of four slab-on-grade houses using sub-slab suction from outdoors, even though forced-air heating supply ducts under the slabs appeared to prevent effective extension of the suction field under the slab. Forced-air exhaust of the crawl space in four crawl-space houses proved more effective in reducing radon in the living area than did natural ventilation of the crawl space. Closure of the wall/floor joint in two basement houses with concrete foundations, and of a sump in one house, appeared to give moderate reductions in the house with the sump, but limited reduction in the other. Operation of sub-slab ventilation systems in suction proved consistently more effective in reducing radon than did operation in pressure.

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TESTING OF INDOOR RADON REDUCTION TECHNIQUES IN CENTRAL OHIO HOUSES:

PHASE 1 (WINTER 1987-1988)

by

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ABSTRACT

Developmental radon reduction techniques were installed in 16 houses near Dayton, Ohio. Soil ventilation by sub-slab suction and sump plus drain-tile suction reduced radon concentrations in five basement houses to below 150 becquerel per cubic meter (Bq/m^3), — or 4 picocuries per liter (pCi/L) — based upon short-term measurements. In one of these houses, airflow in the system was only 2 L/sec (4 cfm).

In two houses that had both a basement plus an adjoining slab-on-grade wing, sub-slab suction in the basement portion alone reduced radon levels in the entire house.

In four slab-on-grade houses with forced-air heating supply ducts beneath the slabs which divided the sub-slab fill into independent compartments, radon concentrations were reduced by more than 90% by sub-slab suction applied through the foundation wall from outside the house.

Operation of sub-slab ventilation systems in suction proved consistently more effective in reducing radon than did operation of the systems in pressure.

In four crawlspace houses forced exhaust of the crawlspace proved more effective in reducing radon concentrations in the living area than did natural ventilation of the crawlspace.

In two basement houses with solid concrete foundation walls, caulking of the wall/floor joint and a sump in one house gave a moderate reduction of radon concentrations in the house with a sump, but only a small reduction in the other house.

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SECTION 1

INTRODUCTION AND OBJECTIVES

1.1 GENERAL OBJECTIVES

cu. m

The U. S. Environmental Protection Agency (EPA) has a program to demonstrate practical, cost effective methods to reduce indoor radon concentrations in housing to 150 Bq/m^3 (4 pCi/L) or less. The complete program will evaluate the full range of radon reduction methods, i.e., house ventilation, sealing of entry routes, soil ventilation, radon removal from water, and air-cleaning in the full range of housing sub-structure types and building styles, and geological conditions across the continental United States. The program described in this report was to demonstrate certain radon reduction methods in housing and geology typical of southern Ohio in particular, and the central Great Plains States in general. The work was conducted by ACRES INTERNATIONAL CORPORATION of Amherst, New York; assisted by AMERICAN ATCON INC. of Wilmington, Delaware under EPA Contract 68-02-4262.

The testing of radon mitigation systems in Ohio houses is envisioned as taking place in two phases. This report describes Phase 1, which was carried out in 16 existing houses in the Dayton area during the 1987-1988 heating season.

This project was sponsored by EPA, and was carried out under an agreement between EPA, the Ohio Department of Health, and the Dayton Regional Air Pollution Control Agency (RAPCA).

1.2 SPECIFIC OBJECTIVES

The specific objectives of Phase 1 of the Ohio field project were:

1. To verify that sub-slab and sump (drain tile) soil ventilation systems can provide high radon reductions in "pure" basement houses in Ohio (i.e., basement houses having no adjoining slab-on-grade or crawlspace). These active soil ventilation systems have proven very effective in testing in other areas.

2. To demonstrate whether sub-slab ventilation in the basement section alone can reduce radon levels throughout split-level basement houses with adjoining slab-on-grade wings; or if separate vent pipes directly treating the adjoining slab are required.

3. To explore alternative mitigation methods for slab-on-grade houses with forced-air heating distribution ducts underneath the slab.

4. To test alternative methods for treating crawlspace houses, including: natural ventilation of the crawlspace, to dilute the radon in the crawlspace and to reduce the natural forces drawing soil gas into the crawlspace; and forced-air ventilation

of the crawlspace, with the ventilation fan operating to exhaust air from the crawlspace, in an effort to depressurize the crawlspace relative to the living area.

5. To test caulking (closure) alone as a method for reducing radon in basement houses which are particularly amenable to closure of radon entry routes (i.e., poured concrete foundation walls, basement unfinished so that radon entry routes are accessible, and slab and walls reasonably free of cracking). If entry route closure gives good results in such "textbook-case" houses, this would provide an incentive to consider closure in more complex cases.

SECTION 2

SUMMARY AND CONCLUSIONS

2.1 OBJECTIVE 1 — SUB-SLAB VENTILATION AND SUMP VENTILATION IN BASEMENT HOUSES

1. In the 3 basement houses without sumps (Houses 7, 43 and 45), minimal active sub-slab suction systems with only a single suction pipe through the basement slab achieved radon reductions greater than 90%, consistent with experience in other areas where sub-slab communication was as good as that in the Dayton houses. In these 3 houses, initial radon concentrations ranging from 370 to 710 Bq/m^3 (10.0 to 19.2 pCi/L) in the basement, based upon winter alpha-track measurements, were reduced to 18 to 100 Bq/m^3 (0.5 to 2.6 pCi/L), based upon 4-day Pylon measurements during cold weather immediately following system activation.

2. In House 43, the suction pipe was placed at one end of a large basement slab (170 m^2, or 1850 ft^2). Thus, where communication is good, high reductions can be achieved with a limited number of suction pipes and with reasonable flexibility in pipe location. (The fans in these installations were capable of 127 L/sec (270 cfm) at zero static pressure, and could develop 350 Pa (1.4 in. H_2O) suction at zero flow).

3. The sub-slab suction systems in Houses 7 and 43 gave high reductions despite unusually low flow rates — 2 L/sec (4 cfm) in House 7, 10 L/sec (22 cfm) in House 43. High flows are not necessary to obtain high radon reductions, as long as the suction field extends under all the slab. Pre-mitigation sub-slab communication tests suggested that high flows would be expected in these houses, indicating that the pre-mitigation testing does not completely predict the performance of the installed system.

4. In the 2 basement houses with sumps and soil drain loops (Houses 4 and 32), active sump suction achieved radon reductions greater than 95%, again consistent with experience elsewhere when sub-slab communication was good. In these 2 houses, initial radon concentrations of 860 to 910 Bq/m^3 (23.2 to 24.5 pCi/L) in the basement were reduced to 18 to 45 Bq/m^3 (0.5 to 1.2 pCi/L).

5. Operation of all these active soil ventilation systems with the fans in suction was always distinctly superior to operation with the fans reversed to pressurize the sub-slab region. Reductions of 80 to 96% with the fans in suction fell to 47 to 89% with the fans in pressure. Sub-slab pressurization depends upon creation of a good flow of air under the slab, to dilute the radon in the gas under the slab, since pressurization will by definition force sub-slab gas up into the house. Since flows are not high in many of these houses, and are unusually low in some cases, it is not surprising that the performance in pressurization was not as good.

2.2 OBJECTIVE 2 — SUB-SLAB VENTILATION IN THE BASEMENT OF BASEMENT PLUS SLAB-ON-GRADE HOUSES

1. Sub-slab suction in the basements of the 2 basement-plus-slab-on-grade houses (Houses 11 and 21) effectively reduced radon levels throughout the houses. Basement concentrations of 1,070 to 3,650 Bq/m^3 (28.9 to 98.6 pCi/L) prior to mitigation, based upon alpha-track measurements, were reduced to 45 to 150 Bq/m^3 (1.2 to 4.0 pCi/L), based upon short-term Pylon measurements. These reductions are expected in view of the good communication measured underneath the basement slab. Upstairs concentrations (on the adjoining slab on grade) were reduced from 470 - 640 Bq/m^3 (12.7 - 17.3 pCi/L) to 35 - 40 Bq/m^3 (0.9 - 1.1 pCi/L).

2. It is not possible to be certain whether the radon reductions upstairs were in fact due to extension of the basement suction field under the adjoining slab, thus treating the entry routes associated with that slab; or whether the observed upstairs reductions resulted only because reductions in the basement reduced the amount of radon migrating upstairs from the basement.

3. Both of these houses had solid foundation walls (the basement walls in House 21 were block filled with concrete), so there were no easy flow paths into the soil as would be the case with hollow concrete block walls. This makes it more likely that the basement sub-slab suction field extends under the adjoining slab in these houses.

4. Despite good pre-mitigation sub-slab communication test results in the basements of both houses, one suction pipe was just sufficient to reduce levels to 150 Bq/m^3 (4 pCi/L) in both houses. In view of the good communication, the powerful fan and the small-to-moderate size of these basements, better performance was expected. In House 11, a second suction pipe was added, located based upon post-mitigation sub-slab suction field extension measurements, reducing basement levels to 45 Bq/m^3 (1.2 pCi/L). System flows in both houses were low, especially in House 21 (where the flows were 2 L/sec, or 4 cfm, similar to the flows observed in House 7), despite good pre-mitigation sub-slab communication results which had led to expectation of greater flows.

5. As with the "pure" basement houses in Objective 1, reversal of the fan to pressurize the sub-slab in House 11 resulted in distinctly poorer radon reductions than when the fan operated in suction.

2.3 OBJECTIVE 3 — SLAB-ON-GRADE HOUSES (WITH SUB-SLAB HEATING DUCTS)

1. Initial efforts in the 4 slab-on-grade houses (Houses 1, 15, 31 and 47) involved continuous operation of the central furnace fan, in an effort to pressurize the sub-slab fill via the forced-air heating supply ducts underneath the slab. This approach resulted in moderate radon reductions (51 - 74%) in Houses 15 and 47, and little, if any, effect on the other two houses. Sub-slab pressure field measurements confirmed that central fan operation increased the sub-slab pressures at all of the test holes.

2. The second effort in the slab-on-grade houses was to close the major accessible opening through the slab, namely, the opening under the bathtub where the bath plumbing comes up through the slab. This step was not expected to be sufficient to reduce radon below 150 Bq/m^3, in view of the other slab openings left unclosed (such as the heating supply registers and the inaccessible wall/floor joint). However, this approach was tested as a measure which homeowners could easily implement themselves. Closing the bathtub opening appeared to give limited radon reductions (31 - 49%) in Houses 15, 31, and 47. (House 1 had no opening under the bathtub.)

Closure of the bathtub opening improved the radon reduction effectiveness of central fan operation in these three houses; in Houses 15 and 47, where fan operation had a significant effect prior to closure, radon reductions with fan operation increased to 67 - 94% after closure.

3. A simple sub-slab ventilation approach proved very effective in all four slab-on-grade houses, even though the sub-slab heating ducts were clearly preventing effective distribution of the suction field in the fill beneath the slab. This approach involved mounting a 127 L/sec fan over a single hole cored horizontally through the foundation wall from outdoors, below slab level. This hole was cored either at one end of the house, or near the middle of the rear of the house. This sub-slab suction approach reduced the pre-mitigation concentrations — which ranged from 470 to 890 Bq/m^3 (12.6 to 24.1 pCi/L) in the four houses, based upon alpha-track measurements and confirmed by Pylon data — to 18 to 50 Bq/m^3 (0.5 to 1.3 pCi/L), based upon Pylon measurements.

4. Of these sub-slab suction results, the results from House 1 are the most tentative. Continuous operation of the central furnace fan — which would tend to counteract the suction field by blowing house air underneath the slab through the heating ducts — increased indoor radon concentrations in House 1 to 390 Bq/m^3 (10.6 pCi/L) with the sub-slab system operating, suggesting that the measured post-mitigation concentration of 50 Bq/m^3 might not hold if the mitigation system is challenged by frequent fan operation in the coldest weather or at the peak of the air-conditioning season. In none of the other three houses did central fan operation cause levels to increase above 150 Bq/m^3 with the sub-slab system operating. House 1 is the only one of the slab-on-grade houses having a hollow-block foundation; the block cores could be facilitating the short-circuiting of house air into the sub-slab system, reducing the development of suction under the slab. Another possible factor is that House 1 is the largest of the four houses; at 185 m^2, or 2,000 ft^2, of slab area, this house is twice as large as the others. Perhaps a single suction point is insufficient with a slab of this size when sub-slab heating ducts are present.

5. Reversal of the sub-slab ventilation fan to operate in pressure distinctly decreased the performance of these systems, relative to operation in suction.

6. Future testing on slab-on-grade houses under Phase 2 of this project will address variables which could not be fully assessed under Phase 1, in part due to the limited number of houses tested. These variables include house construction variables such as: hollow-block versus poured concrete foundations; house size; the presence or absence of sub-slab heating ducts; the configuration of the sub-slab heating ducts (i.e., radial or circumferential); and the presence or absence of sunken living rooms. In addition, other mitigation approaches to be tested include: sub-slab suction pipes through the slab from inside the house (in addition to horizontally through the foundation wall from outdoors); and "site ventilation", defined here as suction on vertical pipes embedded in the ground outside the house, in an effort divert soil gas away from the house.

2.4 OBJECTIVE 4 — CRAWLSPACE HOUSES

1. Initially, the 4 crawlspace houses (Houses 22, 24, 28 and 33) were tested using natural ventilation of the crawlspace as the mitigation approach. These houses had from 3 to 7 foundation vents around the perimeter of the crawlspace foundation wall. Indoor radon levels were measured with these vents open and closed, in an effort to reduce indoor levels by diluting the radon concentrations in the crawlspace and by reducing the forces drawing soil gas up out of the soil. Opening the vents caused reductions of 37 to 84% in the concentrations in the living area, and reductions of 56 to 91% in the concentrations in the crawlspace. Living area

180 to 670 Bq/m^3 (5.0 to 18.2 pCi/L) measured with Pylons just before the vents were opened, were reduced to 100 to 340 Bq/m^3 (2.7 to 9.1 pCi/L) when the vents were opened.

2. The houses were also tested with forced exhaust ventilation of the crawlspace. In addition to increasing ventilation, forced-air exhaust was expected to depressurize the crawlspace relative to the living area, thus reducing migration of crawlspace air containing radon into the living area. To increase crawlspace depressurization, the foundation vents were closed during forced exhaust ventilation; however, no additional air-tightening of the crawlspace foundation wall or of the living space subfloor was attempted. In all four houses, radon levels in the living area were reduced to a significantly greater extent by forced exhaust than by natural ventilation of the crawlspace. Reductions in the living area with forced exhaust were 69 to 93%, reducing indoor concentrations to 30 - 180 Bq/m^3 (0.8 - 4.8 pCi/L). However, reductions in crawlspace concentrations with forced ventilation (8 - 50%) were distinctly poorer than with natural ventilation. This was expected for depressurizing the crawlspace draws more soil gas into the crawlspace, largely offsetting the increased ventilation. The potential of the crawlspace depressurization mechanism is demonstrated by the fact that concentrations in the living area can be substantially decreased while the crawlspace concentrations are being decreased only slightly to moderately.

3. Future testing of crawlspace houses under Phase 2 of this project will address mitigation system variables that could not be assessed during Phase 1. These variables include: forced-air ventilation of the crawlspace with the fan oriented to pressurize the crawlspace; placement of a plastic liner over the crawlspace soil and ventilating under the liner, with adjustments to the extent of the liner and to the degree of sealing at the joints; and "site ventilation", as defined above.

1.5 OBJECTIVE 5 — CAULKING (CLOSURE) ALONE IN "TEXTBOOK-CASE" BASEMENT HOUSES

1. In House 32, closure of the sump, caulking of the wall/floor joint and caulking around utility line penetrations resulted in a radon reduction of about 62% in the basement, reducing basement concentrations from 860 Bq/m^3 (23.2 pCi/L) to 380 Bq/m^3 (10.2 pCi/L). In House 49, which had no sump, caulking of the wall/floor joint appeared to result in no significant reduction. The pre-mitigation measurement in House 49 was 210 Bq/m^3 (5.8 pCi/L), and the post-mitigation measurement was 160 Bq/m^3 (4.4 pCi/L), well within the variability of the levels seen in the Dayton houses. The more clear-cut reduction in House 32 probably reflects the significance of sumps as radon entry routes.

2. The wall/floor joints were closed using gun-grade polyurethane caulk after wire-brushing and carefully cleaning the surfaces. Flowable urethane caulk was tried, but disappeared down the 1 - 3 mm (1/32 - 1/8 in.) wide wall/floor crack. The sump was closed using a circular acrylic plastic cover cut to fit the sump opening, caulked around the perimeter and around the sump penetrations (water discharge line, electrical connection to pump).

3. Diagnostic testing indicates that radon is still entering the houses through the wall/floor joint, despite the fact that the caulk bead appears to be adhering well to both the concrete foundation wall and the slab. One hypothesis is that the soil gas is bypassing the caulk bead, by moving through the porous surface of the concrete (the "laitance") near the base of the foundation wall. If this is correct, and if a suitable primer will not close the laitance, then the reductions that can be achieved using the type of caulking effort that homeowners could reasonably perform by themselves can be expected to be small.

SECTION 3

HOUSE SELECTION PROCEDURE

The first step of this field project was to select between 15 and 20 existing houses to serve as the study houses for the project. A three-step house selection process was utilized. As described below, the selection steps included: 1) a paper screening, using an existing data base which contained radon measurements and house profile information on about 4,300 houses; 2) 30-minute walk-through visits to 50 candidate houses identified from the paper screening; and 3) extended 2-hour visits to the candidates remaining after the walk-throughs, when various tests and measurements were carried out to enable final selection. This three-step selection procedure enabled identification of study houses which met EPA's test objectives in a manner which minimized the impact on the homeowners and most effectively utilized the efforts of the selection team.

Using this approach, 16 houses in the Dayton area were selected for testing in the Phase 1 program. Information on these houses — including the radon measurements made prior to the start of mitigation work — are listed in Tables 1, 2, 3 of Appendix A.

3.1 HOUSE SELECTION CRITERIA

Eleven house selection criteria were designated to ensure that the selected houses would enable the test objectives to be met. These criteria are listed below, together with the step in the selection process (as defined above) during which the criterion was addressed.

Criterion	Selection Steps Where Criterion Addressed
1. House substructure meets objectives	
- pure basement, slab-on-grade, crawlspace, basement plus slab-on-grade	1 and 2
- foundation wall — block or poured concrete	2
2. House reasonably representative of other houses of its type	2
3. Radon concentration meets objectives — about 750 Bq/m^3 (20 pCi/L) or higher for basement houses; about 370 Bq/m^3 (10 pCi/L) for slab and crawlspace houses	1 and 3
4. House location reasonably convenient	1 and 2
5. House no more than 35-40 years old	1 and 2

6. House not unnecessarily difficult to work in (e.g., not unusually large or heavily finished)	2
7. Homeowners amenable to hosting a development project	2
8. House accessible during work day	2
9. Radon results from soil gas entry, and not from well water or building materials	3
10. Sub-slab communication covers range from good to poor	3
11. House has construction features necessary to meet objectives (e.g., has sump and full or partial loop of drain tiles)	1, 2 and 3

3.2 AVAILABLE DATA BASE

The data base arose from a charcoal-packet radon survey conducted in the Dayton area over the winter of 1986-87, involving the distribution of approximately 15,000 charcoal detectors. The survey was promoted by a Dayton television station (WHIO-Channel 7). In an effort to obtain house profile information to supplement these radon measurements, the Dayton Regional Air Pollution Control Agency sent questionnaires to the participants in the WHIO survey. A total of 5,871 of the survey participants returned the questionnaire, providing information on the house substructure, house age, sampling location, and other features. This information, along with the reported radon concentration and the house zip code, were entered into a computerized data base.

The reported radon concentrations in this 5,871-house data base were approximately log-normally distributed with a median of 150 Bq/m^3 (4 pCi/L), and a geometric standard deviation of 2.5. About 4% of the measurements were above 750 Bq/m^3 (20 pCi/L), and 0.6% (35 houses) had readings above 1,800 Bq/m^3 (50 pCi/L).

For the purposes of the paper screening conducted as part of the house selection process for this project, the data base was modified to remove those houses where the RAPCA questionnaire had not been fully completed by the homeowner. The resulting modified data base consisted of 4,298 houses. As with the parent data base, the reported radon levels in the modified data base were approximately log-normally distributed, with a median of 130 Bq/m^3 and a geometric standard deviation of 2.7. About 3.6% of the measurements were over 750 Bq/m^3. A summary of the 4,298-house data base is presented in Table I.

3.3 FIRST STEP IN HOUSE SELECTION - PAPER SCREENING

The data base contained sufficient information to permit the 4,298 houses to be screened for a number of the selection criteria.

- basic house substructure (basement, slab-on-grade, or crawlspace).
- radon concentration, as reported from the charcoal packet survey.

- general location of the house from the zip code. The 33 selected zip codes covered the eastern half of the WHIO broadcast area, out to a radius of about 25 km (16 miles) from Dayton. This appeared to be the most convenient area in which to conduct the project, due to good road connections.

- house age.

- the presence or absence of a sump (since it was desired to test sump ventilation in some of the cases for Objective 1).

When the data base was sorted based upon these selection criteria, 105 of the 4,298 houses met the criteria.

These 105 homeowners were contacted to ask if they would like to be candidates for inclusion in this project. To protect the homeowners' identity, the houses in the data base were identified only by a code number (which corresponded to the identification number of the charcoal detector). The actual identities of the homeowners were known only by the detector supplier, Air Chek, Inc. EPA and RAPCA made arrangements with Air Chek for Air Chek to send letters to the 105 homeowners, advising them of this project and requesting that they return a form authorizing the release of their identities to EPA's contractor if they wished to be considered for the project. By late November 1987, 50 of the homeowners had returned the forms. This response rate of about 50% is consistent with response rates observed in similar field projects.

Table I. DISTRIBUTION OF HOUSE TYPE AND RADON LEVEL IN DATA BASE

Housing Type	Number of houses	Number (%) over 750 Bq/m^3
Basement only - with sump	978	51 (5.2%)
Basement - sump and crawlspace	420	23 (5.5%)
Total - Basements with sump	1,398	74 (5.2%)
Basement only - no sump	1,299	41 (3.2%)
Basement and crawlspace	386	21 (5.4%)
Total - Basements without sump	1,685	62 (3.6%)
Slab-on-grade	913	20 (2.2%)
Crawl-space	302	14 (4.6%)

3.4 SECOND STEP IN HOUSE SELECTION - WALK-THROUGH VISITS

All 50 candidate houses received a 30-minute walk-through visit during the week of December 7-11, 1987, by a team including representatives from EPA, from EPA's contractor, from RAPCA, and from the Ohio Department of Health. Appointments with the homeowners had been made by RAPCA, and RAPCA personnel guided the visitation team between houses, greatly increasing the efficiency of the visits.

Each walk-through visit involved a visual inspection of the house and discussions with the homeowners. To aid the inspection, a simplified inspection form was filled out, focussing on house features of particular importance in view of project objectives, and photographs were taken of distinctive house features. No measurements were made during these visits. To maintain confidentiality, each house was assigned an identification number, which corresponded to the order in which the house was visited among the 50.

One purpose of the walk-through visits was to obtain information about the house which was not available from the data base. Selection criteria addressed during the walk-throughs which could not be assessed from the data base included:

- the material of construction of the foundation walls (particularly important for Objective 5, but also considered in selection for the other objectives as well, to ensure a representative mix);
- the representativeness of the house, compared to other houses of its type that had been visited;
- any unnecessary difficulties that the house might present, complicating achievement of EPA's objectives or unnecessarily increasing project costs;
- the amenability of the homeowners, as determined from discussions with them;
- the accessibility of the house during the work day;
- specific house construction features of interest, e.g., whether drain tiles could be seen entering sumps.

Another purpose of the visits was to verify information in the data base. The information in the data base was occasionally found during the visit to be incorrect or misleading (e.g., concerning house substructure or age). For example, several houses listed in the data base as pure basement houses were in fact combination substructures (basements with adjoining slabs on grade or crawlspaces), because the homeowner was uncertain how to describe the house in the house profile questionnaire.

During the visit, the location of the charcoal detector measurement was verified. Although the written instructions included with the detector specified that it should be placed centrally within livable area, preferably in the lowest livable area of the house, some homeowners placed the detectors in sumps, in crawlspaces, in slab openings under bathtubs in slab-on-grade houses, etc. This was done under the belief — apparently prompted by reports in some local news media — that it was desirable to identify the highest radon concentration in the house, even if this meant placing the detector in non-livable area. The detector placement — and, consequently, the probable representativeness of the charcoal measurement in reflecting concentrations in the livable area — was considered during the selection process.

The walk-through visits also provided perspectives of the Dayton area housing stock which aided in the selection process. The large number of slab-on-grade houses visited with heating ducts under the slab resulted in increased emphasis on Objective 3 in the project; the observed number of basement-plus-slab-on-grade split-level houses led to the inclusion of Objective 2.

Another perspective gained during the walk-throughs was the distribution of geological characteristics. The surface layer of heavy clay soil was sometimes underlain by gravel and sometimes by fractured limestone, and so an effort was made to select houses representing both geological situations.

During the visit, an EPA representative on the team sat down with the homeowner to describe the nature of the envisioned project, the project objectives, the project schedule, and the nature of the mitigation system that would be installed in the house if the house were selected. Any questions by the homeowner were answered. This discussion not only informed the homeowner, but also provided an opportunity for the team to inquire regarding house accessibility and regarding house features which were not visible (e.g., regarding the nature of the aggregate under the slab or the extent of drain tiles emptying into the sump, in cases where the owner had seen the house built). From these discussions, the team could also obtain an initial assessment of the general amenability of the owner.

Based upon the observations during these walk-through visits, 26 of the 50 houses were felt to meet those house selection criteria which could be assessed by visual inspection. Further measurements would be necessary to permit final selection of those houses to be included in the project. A breakdown of these 26 houses is presented in Table II.

Table II. HOUSES REMAINING AS CANDIDATES FOLLOWING WALK-THROUGH VISITS

House Type	Number of houses
Basement	
with sump	6
without sump	4
Basement plus slab-on-grade	
with sump	2
without sump	3
Slab-on-grade	5
Crawlspace	6

Soon after the walk-through visits were completed, one of the 26 candidates withdrew from consideration. Thus, 25 candidates remained as the third step of the selection process was initiated.

It was desired to obtain a pre-mitigation alpha-track detector radon measurement over several weeks in the project houses during the heating season. Such a measurement would provide a more reliable basis for evaluating ultimate mitigation performance than would the 2 to 4 day charcoal measurements on which the selection had been made. To obtain at least 8 weeks of heating season pre-mitigation data, it was necessary that the alpha-track detectors be deployed in all 25 remaining candidate houses immediately following the walk-through visits, even though it was recognized that not all of these would be selected for inclusion in the project. The ultimate house selection steps would not take place until January 1988, and since mitigation installations were to begin in February 1988, there would not be enough time to obtain a good pre-mitigation measurement if deployment of the alpha-track detectors was delayed until the final selection was made. Thus, on December 17 and 18, detectors were placed in all 25 remaining candidates, in both the main living area and in the basement or crawlspace, as applicable. These detectors were subsequently retrieved from each house before mitigation work started in that house or in April 1988, in the case of those houses which were not selected for inclusion in the project.

3.5 THIRD STEP IN HOUSE SELECTION - DIAGNOSTIC TESTING VISITS

To enable the final selection of study houses from among the 25 remaining candidates, tests were conducted in each house, to determine which houses would best enable EPA's objectives to be met. The nature of these tests varied from house to house, depending upon which objective the given house was intended to address.

In every house, a radon measurement was made using a continuous radon monitor, for a period of 24 to 98 hours, to confirm the available charcoal detector measurement. Confirmation of the charcoal measurement was felt to be important because some of the charcoal detectors had been placed in non-livable areas by the homeowners. It was felt important that the radon level in the living area be at least as high as that indicated in the selection criteria (Section 3.1), since it is hard to measure the effectiveness of the mitigation system when the pre-mitigation radon concentrations are not distinctly elevated. These short-term Pylon continuous radon measurements were made in the 25 candidate houses during the month of January 1988. As shown in Table 1 of Appendix A, these pre-selection continuous radon monitor measurements generally compare well with the charcoal data, considering that both are short-term measurements.

These confirmatory radon measurements were the only pre-selection measurements which were felt to be necessary for the houses being considered for Objectives 3 (slab-on-grade), 4 (crawlspace), and 5 (sealing). Little testing had been conducted to date toward any of these objectives, so that the candidate houses would be of interest irrespective of the results of diagnostic tests (such as sub-slab communication and permeabilty measurements). In addition, other tests which could be conducted during a relatively brief visit would not provide results to facilitate a definitive selection between these candidate houses. For example, it was apparent beforehand that sub-slab measurements would show poor communication under all of the slab-on-grade houses with heating ducts under the slab; hence, pre-selection sub-slab communication measurements in the slab-on-grade houses at this stage would not provide any additional basis for selection between the houses. (Of course, such measurements would ultimately be necessary after selection to aid in the interpretation of mitigation results). Thus, it was intended that all of the slab-on-grade, crawlspace and sealing candidates remaining after Step 2 of the selection process would be included in the project if they met the radon concentration criterion. As it turned out, 1 of the slab-on-grade houses, 2 of the crawlspace houses, and none of the concrete basement houses for sealing were dropped from consideration for the project when the short-term pylon measurements averaged 370 Bq/m^3 or more in the living area.

For the basement and the basement-plus-slab-on-grade houses which were candidates for Objectives 1 and 2, sub-slab communication testing in addition to radon measurements was considered necessary prior to selection. It was desired to select some houses with poor sub-slab communication as well as some with good communication, so that the effect of communication on system design and performance could be evaluated. Accordingly, during the week of January 11 to 15, 1988, a team visited all of the remaining candidate houses for Objectives 1 and 2, and conducted sub-slab communication tests. This team included representatives of EPA, EPA's contractor, RAPCA and the Ohio Department of Health.

The methodology for the communication testing is described in Section 5, "Measurement Procedures". The diagnostic testing conducted during these visits included, in addition to communication testing: grab sampling underneath the slab and at other appropriate locations for radon gas analysis to assess entry routes; gamma radiation measurements, to assess building materials and water as possible radon sources; and collection of well water samples, where applicable, to assess well water as a possible radon source. The water samples were analyzed by the Ohio Department of Health. In addition to these tests, a comprehensive EPA house survey form was completed for each house visited. The results of these diagnostic tests are included in the detailed descriptions of results for each house, presented in Appendix C. One of the basement houses could not be visited during the week of January 11 because the owner was on vacation.

As it turned out, sub-slab communication was good to excellent in all of the candidate basement houses. Building materials and well water were not significant radon sources in any of the houses. Thus, these diagnostic results did not provide any additional basis for selecting among the candidates for Objectives 1 and 2. Accordingly — as in the case of Objectives 3, 4 and 5 — the final selection of the Objective 1 and 2 study houses for this project was made solely on the basis of the Pylon radon measurement. Three of the candidate houses for Objective 1, and 3 of the candidates for Objective 2, were dropped from consideration because the Pylon measurements averaged less than 370 Bq/m^3.

3.6 SELECTION OF HOUSES FOR INCLUSION IN PROJECT

At the conclusion of Step 3 in the selection process, there were 16 remaining houses which were selected for inclusion in the project. These 16 houses are listed in Table III.

Table III. HOUSES SELECTED FOR THE PROGRAM

House ID #	Type	Location	Survey Reading Bq/m^3	(pCi/L)	Objective
1	S	Beavercreek	600	(16)	3
4	B	Springfield	1,700	(46)	1A
7	B	Springfield	1,000	(27)	1B
11	B/S	Spring Valley	1,100	(29)	2
15	S	Xenia	1,000	(27)	3
21	B/S	Xenia	3,400	(93)	2
22	CS	Troy	850	(23)	4
24	CS	Troy	1,900	(51)	4
28	CS	Tipp City	700	(19)	4
31	S	Fairborn	650	(18)	3
32	B	Fairborn	1,400	(38)	1A,5
33	CS	Fairborn	650	(18)	4
43	B	Kettering	850	(23)	1B
45	B	Dayton	4,300	(117)	1B
47	S	Dayton	800	(21)	3
49	B	Bellbrook	350	(9)	5

The house type codes are:-
B = basement; B/S = basement plus slab-on-grade; S = slab-on-grade, CS = crawlspace.

Further data on the selected houses are presented in Appendix A. Table 2 lists house structural features, house location and the arithmetic mean of the charcoal detector survey data and the January pre-selection Pylon radon measurements. Table 3 presents the pre-mitigation alpha-track detector results in each of the 16 houses, plus the average of all pre-mitigation Pylon measurements in the houses including Pylon measurements in addition to those made in January prior to selection.

SECTION 4

DESCRIPTION OF MITIGATION SYSTEMS

4.1 ACTIVE SOIL VENTILATION SYSTEMS

The radon reduction method tested in the basement and slab-on-grade houses was active soil ventilation. This method was selected because it appeared to be the approach most likely to provide large reductions in radon concentration at a reasonable cost.

The general principle of soil ventilation systems is to change the pressure in the soil adjacent to the building foundations to divert the radon-bearing soil gas away from the house before it can enter. When fans are employed to produce the pressure change, the approach is referred to as *active* soil ventilation. The systems can be used to either a) draw suction on the soil around the foundation to collect soil gas and so divert it from entering the house; or b) to blow outdoor air into the soil, creating a "pressure bubble" underneath the house which forces the soil gas away from the house.

If the active soil ventilation system is operated with the fan in suction, it will be effective if it is able to maintain soil pressures at all of the major soil gas entry routes lower than the air pressure inside the house. Under this condition, if there is any gas movement through those entry routes, it will be house air flowing out rather than soil gas flowing in. If the fan is operated in pressure, blowing outdoor air into the soil, it will be effective only if it can maintain sufficiently high air flows under the slab so that the soil gas is diluted before the sub-slab gas is forced into the house through the entry routes. A number of the installations were operated briefly with the fan in pressure, in order to compare system performance in pressure with the performance in the normal suction mode.

In this project, active soil ventilation was accomplished in several different ways:

- Suction on the perimeter drain located beside the footings for water drainage purposes. In the Dayton houses, these drains were often inside the footings, under the slab (interior drain tiles); sometimes there was also a drain on the outside of the footings (exterior tiles). In Houses 4 and 32, the drains were connected to a sump inside the house; thus, suction on the drain was carried out by suction on the sump as shown in Figure 1. This was the system tested for Objective 1A.

- Suction on the region underneath the concrete floor slab of basement houses, by inserting suction pipes vertically downward through the slab from inside the house as shown in Figure 2. This was the system utilized in Houses 7, 43 and 45 (Objective 1B) and in the basements of Houses 11 and 21 (Objective 2).

- Suction on the region underneath the floor slab of slab-on-grade houses by attaching a fan directly to a horizontal opening through the foundation wall below the house floor slab from outside the house, as shown in Figure 3. This was the type of system installed on slab-on-grade Houses 1, 15, 31 and 47 (Objective 3), following tests of sub-slab pressurization by continuous operation of the central furnace fan, and closure of accessible slab openings.

Most of the installations made under this project differ in some details from these generic figures.

4.2 CRAWLSPACE VENTILATION

Crawlspace houses are naturally isolated from the soil by the barrier of the crawlspace. Radon can only enter the house by first entering the crawlspace, so if radon concentrations there can be kept low, then radon concentrations in the house will also be low. Radon concentrations can be controlled either by increasing the crawlspace ventilation rate or reducing the radon supply. Alternatively, radon concentrations in the living area will be reduced if the crawlspace can be depressurized relative to the house; under those conditions, the airflow would involve clean house air flowing into the crawlspace rather than radon-containing crawlspace air flowing into the house.

The crawlspace houses in this project all had several adjustable foundation vents in the crawlspace foundation wall. These vents are normally closed during the heating season, so the first line of investigation in these houses was to determine the effect on radon concentrations of changes in natural crawlspace ventilation caused by opening or closing the vents. This would be expected to dilute the radon in the crawlspace.

In addition, forced ventilation of the crawlspace using an exhaust fan was tested. Forced exhaust ventilation would not only dilute the crawlspace radon, but would also depressurize the crawlspace relative to the house. A typical forced-exhaust installation is shown in Figure 4.

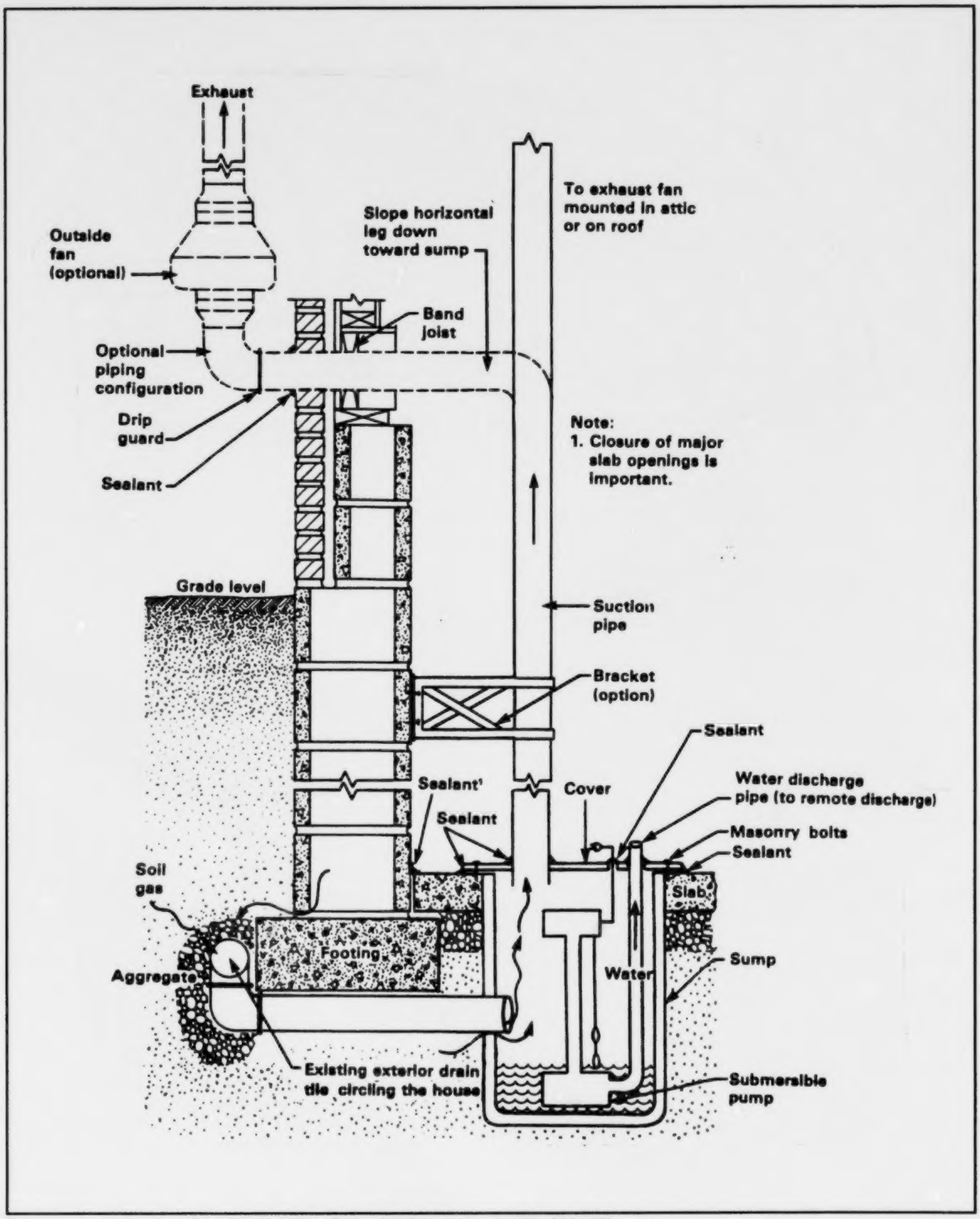

Exhaust
Outside fan (optional)
Slope horizontal leg down toward sump
To exhaust fan mounted in attic or on roof
Band joist
Optional piping configuration
Drip guard
Sealant
Note:
1. Closure of major slab openings is important.
Grade level
Suction pipe
Bracket (option)
Sealant
Water discharge pipe (to remote discharge)
Sealant¹
Cover
Sealant
Masonry bolts
Sealant
Soil gas
Slab
Footing
Aggregate
Water
Sump
Existing exterior drain tile circling the house
Submersible pump

Figure 1. WEEPING-TILE VENTILATION VIA THE SUMP

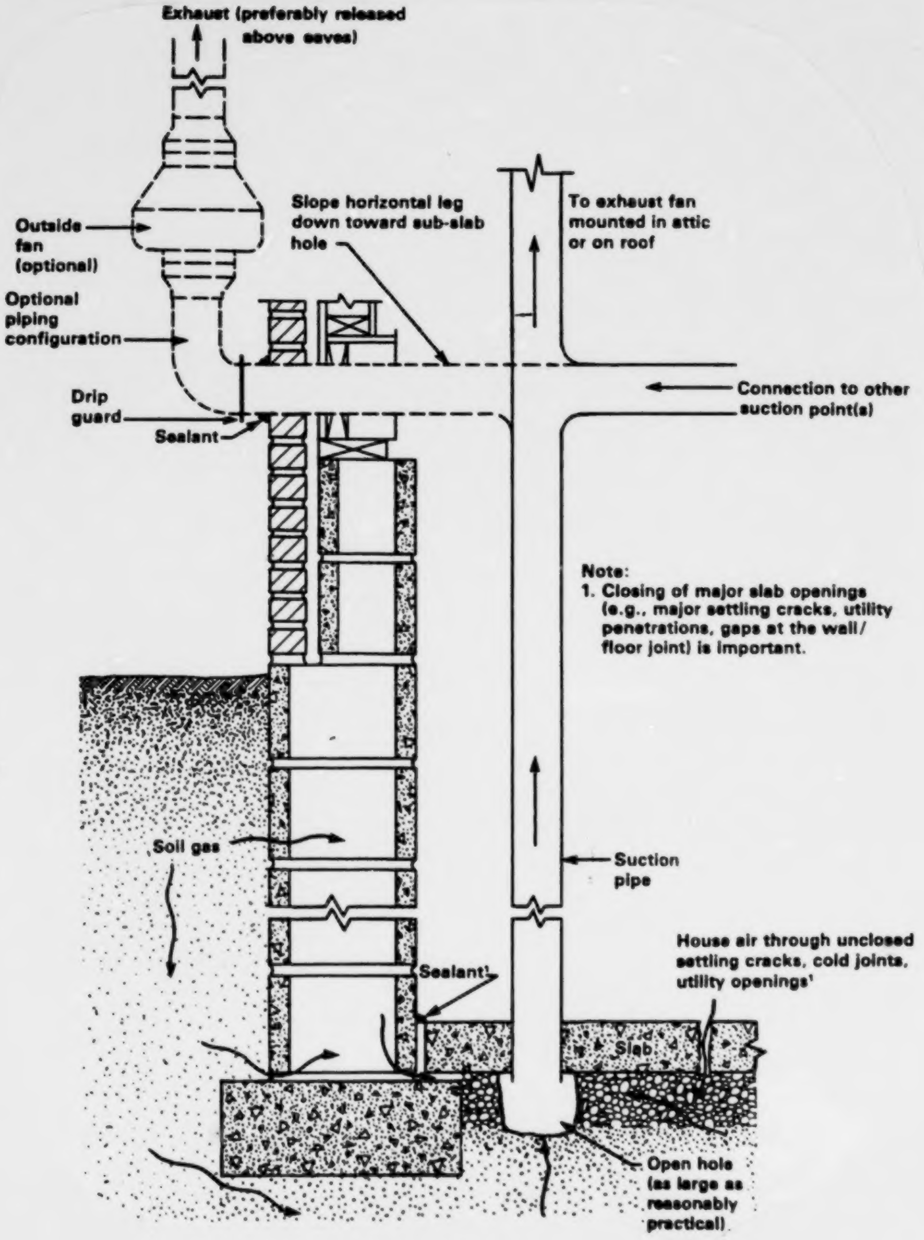

Exhaust (preferably released above eaves)
Outside fan (optional)
Optional piping configuration
Drip guard
Sealant
Slope horizontal leg down toward sub-slab hole
To exhaust fan mounted in attic or on roof
Connection to other suction point(s)
Note:
1. Closing of major slab openings (e.g., major settling cracks, utility penetrations, gaps at the wall/floor joint) is important.
Soil gas
Suction pipe
House air through unclosed settling cracks, cold joints, utility openings¹
Sealant¹
Slab
Open hole (as large as reasonably practical)

Figure 2. SUB-SLAB VENTILATION IN A BASEMENT HOUSE

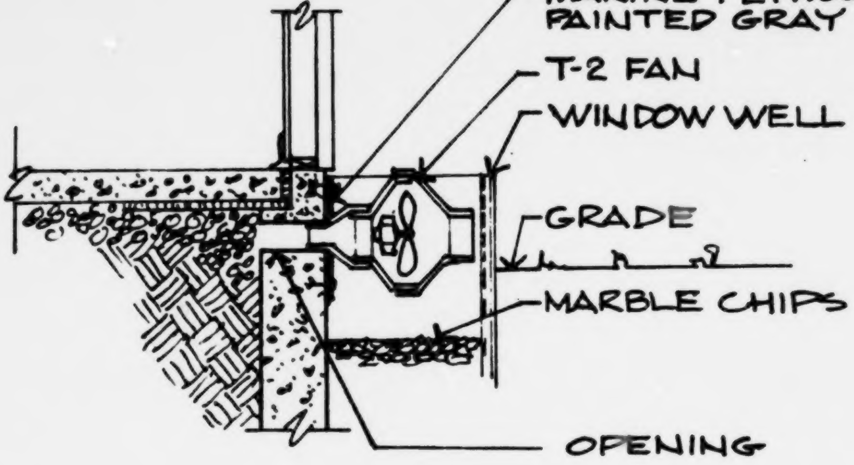


Figure 3. SUB-SLAB VENTILATION IN A SLAB-ON-GRADE HOUSE

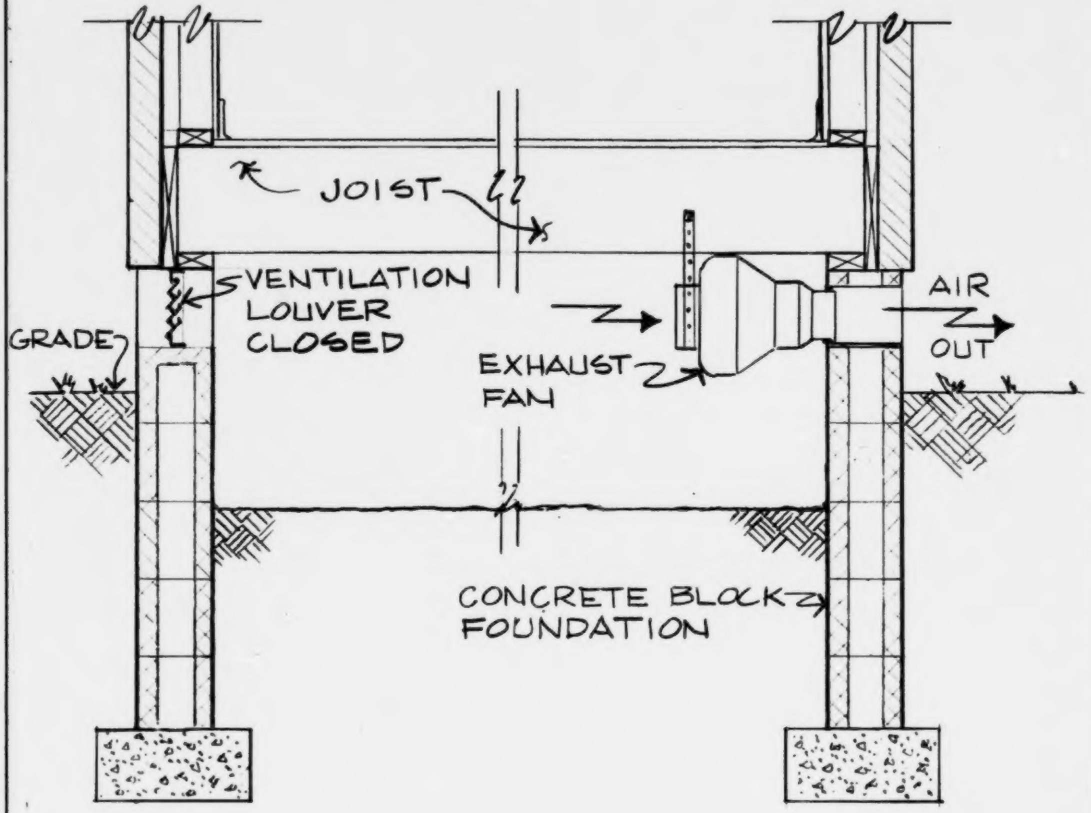


Figure 4. CRAWLSPACE FORCED VENTILATION

SECTION 5

MEASUREMENT PROCEDURES

5.1 RADON MEASUREMENT PROCEDURES

The performance of the radon reduction systems was determined by two types of radon measurements in the indoor air. The first was short-term monitoring for 2 to 4 days with Pylon AB-5 continuous radon monitors both before and after the system was activated. These measurements provided an immediate indication of the approximate reduction in radon concentration, and whether the post-mitigation concentrations had been reduced below 150 Bq/m^3 (4 pCi/L). The second was a long-term measurement over a year using 4 measurement periods of 3 months with alpha track detectors to indicate whether the long-term average exposure to the occupants had been reduced below 150 Bq/m^3.

"Control houses" were not used in this project. First, there was no expectation that the variation of radon concentrations in one house chosen essentially at random would be identical to the variations in another house. Second, an effective mitigation system reduces radon concentrations to a low level and keeps them low. All the houses chosen for this project had radon concentration that were significantly greater than 150 Bq/m^3, and so a change in concentration of the size required can be demonstrated readily with real-time radon concentration measurements. "Controls" are unnecessary to determine if a mitigation system is effective.

5.2 RADON MEASUREMENT GOALS

The goals of the radon measurement effort were to estimate:

a) the long-term average radon concentration with a total measurement uncertainty of less than 80 Bq/m^3 (2 pCi/L).

b) the short-term average radon concentration with a total measurement uncertainty of less than 10%

c) individual radon concentrations with a total measurement uncertainty of less than 20%

5.3 LONG-TERM RADON MEASUREMENTS

The long-term average concentration in a house is estimated by "Track Etch" alpha-track detectors, exposed for at least 3 months. The forces that urge soil gas and radon into a house are at a maximum in cold weather. Given that the project schedule could permit only one 3-month pre-mitigation alpha-track monitoring period prior to the installations, rather than the preferred full year, the pre-mitigation detectors were exposed in the winter months, in order to reflect indoor concentrations under presumably the most challenging conditions. Doors and windows are kept closed during the winter months, so that winter measurements are more likely to be taken under standardized (closed-house) conditions.

A summary of the pre-mitigation alpha track results is given in Table 3 of Appendix A, with further detail in Tables 5 and 6. As indicated previously, post-mitigation alpha-track measurements will be made over a period of one year to provide an estimate of long-term exposure. These results will be presented in a separate report, at the end of the year. The first-quarter post-mitigation results are shown in Tables 7 and 8 of Appendix A.

5.3.1 Detector Location Procedure

Detectors were exposed in groups of three in both the basement (or the crawlspace) and the main living area of the house. The basement detectors were hung centrally, and the upstairs detectors were placed in locations where they would receive an exposure representative of that of the occupants. Locations were chosen to meet the requirements of the EPA "Interim Indoor Radon and Radon Decay Product Measurement Protocols" (EPA-520/1-86-04).

5.3.2 Presentation of Alpha-Track Results

The results of the alpha-track measurements summarized in Table 3 of Appendix A are the arithmetic mean of the three detectors hung in a cluster in a given location. The results from a given detector are not included in calculating the mean only if it is determined to be an outlier. The method for determining outliers, and other quality control steps taken with these detectors, are described in the QA/QC section (Section 13.2).

5.4 SHORT-TERM MEASUREMENTS

The short-term variation of radon concentration with time was measured by a Pylon AB-5 operated as a quasi-continuous radon monitor. An internal pump draws a filtered air sample for 10 minutes each hour into a 285 cm^3 scintillation cell, and five consecutive 10 minute counts are made. In this mode the machine can make 99 consecutive hourly cycles, and the counts are stored internally. The data is subsequently transferred via the printer interface and a specially designed parallel to serial converter to the RS-232 port of a portable computer. A BASIC program sums the counts, and calculates the radon concentration in the sample, and produces a report. The counts observed in each time period are corrected for the counts resulting from activity deposited in the cell by previous samples, so that the actual radon concentration at the sample time is calculated.

To prevent small children from tampering with the machine and altering the settings, each AB-5 is stored and used inside a lockable foam lined aluminum travel case. Two holes are drilled in the case, one for a sample hose to bring in the air, the other for the power cord, so that the machine can operate with the case closed and locked.

A bulkhead connector is placed on one end of the handle face of the case, and the AB-5 inlet hose is attached to this on the inside of the case through an in-line filter. A rigid plastic tube screwed into the connector. When the case is stood with the handle uppermost, the top of the tube is 50 cm from the ground. If the case stands at right angles to a wall, the sample tube is 50 cm from the wall.

5.4.1 Sampler Location Procedure

The standard procedure in basement houses was to place the AB-5 in the basement, close the windows and the stair door to standardize the ventilation rate, and measure the radon concentration over the next 96 hours. A state of quasi-equilibrium between radon supply and removal was usually reached in less than 24 hours. The mitigation system was then turned on or off, depending on the test being made, and measurements continued for another 96 hours. The systems normally develop most of their effect within 24 hours. In all cases, the Pylon was placed at least 50 cm from the floor or wall, 1.5 m from fireplaces, windows or HVAC vents, 2.5 m from exterior doors, and away from radon entry routes, in accordance with the EPA Measurement Protocol.

This procedure was modified for slab-on-grade and crawlspace houses. In slab-on-grade houses, all measurements were necessarily made in the main occupied parts of the house. The measurement area could not be isolated from perturbations resulting from occupant activities as easily as in basement houses, but an attempt was made to locate the monitor in an infrequently used room. In crawlspace houses, measurements were made in both the living area and in the crawlspace. Measurements in the crawlspace were made at 50 cm from the floor and at least 2.5 m from a ventilation opening.

In view of their short-term duration, the AB-5 measurements were not intended to be definitive, but to indicate only whether the mitigative actions taken had significantly reduced the radon supply rate. The effectiveness would not be determined on the basis of short-term measurements over a few days with an AB-5, but would be based on the average concentration over a year obtained with multiple "Track Etch" detectors.

5.4.2 Duration of Pylon Measurements

As indicated above, the Pylon measurements were typically conducted for a 96-hour period with the mitigation system on, and for another 96-hour period with the system off, usually back-to-back. The original intent at the start of the project was for each measurement to be made over a period of about 48 hours. This increase in the length of monitoring was necessary due to the large observed variations in radon levels from day to day. (This is discussed in detail in Reference 2 of Appendix B).

For example, in House 4, pre-mitigation radon levels averaged 3,100 Bq/m^3 (84 pCi/L) over one 24-hour period, 190 Bq/m^3 (5 pCi/L) over the next 24-hour period, and 1,370 Bq/m^3 over the following 48 hours, without any known occupant activities that would have caused this variation (see Figure 04-1 in Appendix C). In House 7, pre-mitigation levels averaged 170 Bq/m^3 (5 pCi/L) over one 48-hour period, and 580 Bq/m^3 (16 pCi/L) over the next 48-hour period (see Figure 07-2 in Appendix C). With this type of variation, it was considered necessary to make the Pylon measurements as long as possible. The duration of 96 hours was as long as could be reasonably achieved, since the Pylon memory limitations prevented it from collecting data over more than 99 consecutive hours, and project schedule and resources prevented a longer monitoring duration.

5.5 INVESTIGATION TEST PROCEDURES

5.5.1 Pre-Mitigation Testing

The primary types of pre-mitigation test activities conducted were:

- Visual survey. This includes inspection of the house to identify potential soil gas entry routes other than hollow concrete block walls and joints in the basement floor slab, and for features that would increase the installation difficulty of particular mitigation systems. This may involve removal of furniture, carpet, appliances, and the use of specialized probes and viewing tools such as a borescope.

- Gamma measurements. These are intended to confirm that building materials are not a major contributor to indoor radon. These measurements were made with a hand-held 5-channel NaI scintillation meter, adjusted to count gamma rays above 400 keV. This gives a reasonably accurate indication of the total ambient gamma radiation.

- Well-water measurements. These are intended to identify the extent to which well-water may be a radon source. A screening measurement was made by checking the radiation field in contact with the hot-water tank. An reading greater than background indicates that the water contains significant amounts of dissolved radon. As a further check, some samples of tap water were collected in an empty sample vial (no "cocktail") in a manner which eliminated air entrainment. These samples were then sent for analysis to the Ohio Department of Health in Columbus.

- Sub-slab permeability and connectivity measurements ("communication"). In basement houses the permeability and connectivity of the material beneath the basement floor slab was determined qualitatively. A high suction (40 inches of water) industrial vacuum cleaner was used to create a suction field under the slab, and the extent and size of the suction field was measured through holes drilled through the slab. The nozzle of the vacuum hose was placed into a 30 mm diameter hole drilled through the slab, and the pressure drop measured by a Magnehelix gauge. Two or more small (9 mm) test holes were drilled through the slab at various locations, including one 0.3 m away from the suction hole, and others remote from the suction hole in different directions, as far away as possible. The pressure drop across the slab at these test holes was measured with electronic pressure sensors or high sensitivity Magnehelix gauges both with and without the vacuum cleaner operating, thus providing a measure of the size and extent of the suction field beneath the slab. (The basis for this test is described in "Radon Reduction Techniques for Detached Houses: Technical Guidance (Second Edition)", EPA/625/5-87-019).

- Spot Radon Measurements. If holes were drilled through the floor for sub-slab permeability measurements, a sample of the sub-slab air was taken before any pressure differentials were applied to give an indication of the natural radon-in-soil-gas concentration.

5.5.2 Post Mitigation Testing

The primary types of post-mitigation testing conducted were:

- Radon in air measurements. The prime indicator that a mitigation system was operating effectively was the radon concentration in the house air. Measurements were made with Pylon semi-continuous radon monitors for 48 to 96 hours before and following activation of any installation or change in a system.

- Visual inspection. This included inspection of the installation to ensure that seals were intact and the fan was properly mounted. As part of this inspection, a smoke stick was used to check the seals in active soil ventilation systems, and that air flows through potential entry routes had in fact been reversed by the suction systems.

- Pressure difference and airflow measurements. The pressure differentials to atmosphere and the airflow rate in each pipe or duct of the active soil ventilation systems were measured using a commercial electronic hot-probe anemometer. A probe adaptor enables the same instrument to read both flow and pressure.

- Spot radon concentrations. Grab samples were taken from each pipe in the active soil ventilation system with a scintillation cell for radon analysis.

- Suction field extension measurements, with active soil ventilation systems in place. Using the test holes drilled through the slab for the pre-mitigation communication testing — and new test holes drilled as warranted — pressure differentials across the slab can be measured with and without the soil ventilation system operating. These measurements confirm how far the system's suction field extends underneath the slab, and the magnitude of the sub-slab suctions being developed by the mitigation system. A high sensitivity Magnehelix gauge was used for these measurements.

- House and crawlspace ventilation rates. As reported in Section 10, perfluorocarbon tracer (PFT) measurements were made in crawlspace houses. These measurements were to determine the effects of natural and forced crawlspace ventilation on the ventilation rates of the living area and the crawlspace, and on the air movement between these two zones.

- Pressure differentials across the house shell. In several cases, (reported in Appendix C), pressure differentials were measured between indoors and outdoors. A high sensitivity Magnehelix gauge was used for these measurements.

SECTION 6

EXPERIENCE WITH SUB-SLAB VENTILATION IN BASEMENT HOUSES (OBJECTIVE 1A)

6.1 GENERAL

Sub-slab ventilation (SSV), as illustrated in Figure 1, has proven to be a very effective radon reduction technique in homes in a number of different areas of the country. Where the home has a "pure" basement substructure, without an adjoining slab-on-grade or crawlspace wing, design of the SSV system is simplified, since entry routes associated with an adjoining wing do not have to be addressed. Based upon the experience elsewhere, it was expected that sub-slab ventilation would give good reductions in basement houses in the Dayton area. The primary intent of Objective 1A was to determine how local house construction practices and geological characteristics of the Dayton area might influence the design and operating conditions needed for successful SSV systems.

Effective application of SSV systems, with the ventilation fan operating to draw suction on the soil, depends upon developing a suction field extending underneath the basement slab to all major soil gas entry routes. The ability to establish this suction field depends upon:—

a) location of sub-slab suction points sufficiently close to the major entry routes;

b) reasonable communication underneath the slab;

c) a fan capable of developing an adequate static pressure at the soil gas flows encountered, so that sufficient suction will be available at openings remote from the suction points;

d) closure of major openings in the slab, so that the suction field is not decreased by leakage of house air into the sub-slab space through these openings.

Three "pure" basement houses were selected to address Objective 1A (Houses 7, 43 and 45). The tests conducted in these 3 houses during the diagnostic testing visits showed that sub-slab connectivity and permeability ranged from moderate to excellent in all of these houses. The suctions measured under the slab at the most remote test hole in the sub-slab communication test — 14 to 35 feet from the industrial vacuum cleaner suction point — was 15 to 30 percent of the value measured in the test hole only one foot from the vacuum. This small decrease in suction with distance indicated that the sub-slab connectivity was excellent. Visual inspection and probes down the holes drilled through the slab for the tests indicated that the slabs were all underlain by 50 to 80 mm of coarse gravel, which would be expected to have low resistance and good communication.

By coincidence, the largest houses had the best sub-slab connectivity and permeability. This excellent communication — together with the high flow and suction capabilities of the fans to be used in these systems — led to the conclusion that only one suction pipe would be needed in each of the Objective 1A houses, regardless of size, and that there would be considerable flexibility in selecting where that pipe should be located. Single-point sub-slab exhaust systems were therefore chosen as the mitigation system to be demonstrated.

A detailed description of the work in these three houses in presented in Appendix C.

6.2 SYSTEM DESIGN AND INSTALLATION

A logical location for a single-point sub-slab exhaust point is in the center of the basement floor, on the basis that this location would make the pressure field beneath the basement floor slab as uniform as possible. A central location was not feasible in these houses. About 2/3 of the basement was finished in Houses 7 and 45, so the exhaust point was located off-center in the storage area. At House 43 the entire basement was finished, and the exhaust point was located in the laundry room at one end of the basement. In view of the good sub-slab communication measured in these houses, it was felt that central location of the suction pipe was not crucial.

The location of the exhaust pipe and fan was discussed and agreed with the owner, and a 12.5 cm diameter hole was made through the basement floor slab by drilling and chipping with an electric hammer-drill. An industrial vacuum cleaner was used to collect the dust as the hole was drilled. The sub-slab fill was removed from the area directly beneath the hole; no other effort was made to excavate a hole in the soil under the suction pipe. Four inch thin-wall PVC pipe was inserted into the hole, and run to the fan. The space between the pipe and the side of the hole was closed with foam backer rod topped with acrylic caulk, which had good adhesion to the concrete.

The ventilation fans used in all of these installations were Kanalflakt T-2 plastic-bodied in-line fans, capable of moving 127 L/sec of air (270 cfm) at zero static pressure, and capable of developing 350 Pa (1.4 in. H_2O) suction at zero flow. The T-2 fan is designed to mount inside a six inch duct, and so 6 to 4-inch light-weight plastic pipe reducers were required to mount the fans on the system piping.

The initial mitigation system installed in each of these houses involved a temporary exhaust fan installation to facilitate the subsequent modification of the system if the initial design did not provide the desired performance. Only after the system had been tested with the temporary fan was the final system installed. For the temporary installation, a basement window was removed, and a fitted plywood panel with a 4 to 6 inch adaptor was placed in the opening. The fan was attached on outside to the 6 inch end of the adaptor with set-screws so that it could be physically reversed to test the system in pressure, and the exhaust pipe was attached to the 4 inch end of the adaptor on the inside.

For the final installations, the SSV piping was routed to the attic in Houses 7 and 43. In House 7, the pipe ran vertically up into the attic through an interior bathroom pipe chase, then was turned 90 degrees to run horizontally through the attic to above the garage, and then through the roof. In House 43, the pipe ran horizontally between the joists of the laundry room ceiling and went out of the basement horizontally through the band joist into the adjoining slab-on-grade garage, entering the garage just above the garage slab; the pipe then ran up through the garage ceiling into the attic and then through the roof. In both houses, the fan was mounted in the attic above the garage, well away from the bedroom area, and the fan exhaust pipe discharged vertically through the roof. In House 45, a route to the attic was not conveniently available; in the final installation the piping exited the basement through a hole cored through the basement wall just above grade level in the back yard; and then ran vertically up the rear wall of the house through the soffit and then to a fan mounted on the roof.

Houses 43 and 45 each had a large connection from the house to the sub-slab space via a floor drain to which soil-drain pipes connected above the water-level in the floor drain trap so that soil gas from the drain tiles could flow into the house via the floor drain. This floor drain/drain tile opening was closed with no loss of drainage function by installing a vertical 2.5 cm (1 inch) diameter dip-tube which extended from the top of the drain level with the floor to below the water level in the trap. The annular space between the dip-tube and the sides of the drain unit was then sealed, so that soil gas could not make its way into the house, but all water entering the floor drain now flowed down the standpipe. For the permanent closure, the annular gap was filled with mortar and caulk. For the temporary installation, the gap was filled with expanding urethane foam.

6.3 PERFORMANCE

The results obtained with the sub-slab ventilation in these three houses are summarized in Table IV. Further details are presented in Appendix C. The radon levels presented in Table IV (both pre-mitigation and post-mitigation) are the short-term Pylon data which provides back-to-back, system on/off comparisons. These measurements were completed by mid-March 1988, when the weather was still cold. The results in the table are with the systems operating in suction, which gives the best performance.

Table IV. PYLON RESULTS FOR SUB-SLAB SUCTION IN BASEMENT HOUSES

	Radon Concentrations in Basement (pCi/L)				
	System Off		System On		
House No.	Range	Mean	Range	Mean	% Reduction in Mean
7	1-29	10.9	1- 6	2.6	76
43	7-25	14.3	0- 1	0.5	96
45	7-30	20.5	1- 3	1.5	93

Note: Radon in Bq/m^3 = 37 x value in pCi/L

As shown in the table, all three of the houses were reduced to mean radon concentrations well below the previous EPA guideline of 150 Bq/m^3 (4 pCi/L). Reductions were above 90% in Houses 43 and 45. These high radon reductions are consistent with the results observed with sub-slab suction in other geographic areas.

The high reductions in House 43 illustrate that — with good sub-slab communication and suitable fan capability — high reductions can be achieved with just one suction pipe, even when the slab is large as 170 m^2 (1850 ft^2), and even when the suction pipe is not centrally located. In this case, the suction pipe 3 m from one end of a large basement slab 9 by 18 m (30 by 62 ft).

The other two houses had slabs of more modest size (approximately 90 m^2, or 1000 ft^2); thus, in those cases, the effectiveness of a single pipe system is less impressive than in the case of House 43.

While the radon reductions in these houses were consistent with what would have been predicted, based upon the good sub-slab communication, the soil gas flows in Houses 7 and 43 were lower than expected from the sub-slab permeability measured during the test. The flow in House 7 (2 L/sec, or 4 cfm) was dramatically low. In this house, the 127 L/sec fan was operating stalled, for the suction in the sub-slab pipe was 350 Pa, (1.4 in. H_2O) — the zero flow value. The flow in House 43 (10 L/sec, or 22 cfm) was not as low, and the suction in the sub-slab pipe of 140 Pa, (0.55" H_2O). The large radon reductions achieved with these low flows confirm that high flows are not necessary to achieve good performance, as long as the suction field covers most of the basement area.

The sub-slab fill material removed from beneath the floor slab during the exhaust pipe installation in House 7 was found to consist of pit-run gravel, with a high proportion of fines, rather than the coarse gravel which it had appeared to be upon visual inspection through the pre-mitigation test holes. Pit-run gravel will have a greater flow resistance than coarse gravel, and the permeability would depend on the working during spreading and leveling the gravel before the slab was poured. The larger stones had apparently been worked to the top of the fill, giving the impression of a coarse stone layer when examined through a test hole drilled in the slab.

It is of interest to speculate why the system flows with the 350 Pa (1.4" H_2O fan) are so different from what was expected from the pre-mitigation communication tests with the 10 kPa (40 " H_2O) industrial vacuum cleaner. With the vacuum cleaner, sub-slab flows had been so great that the vacuum was operating almost flat-out, with little pressure drop in the nozzle, and yet the mitigation system T-2 fan was almost stalled due to low flow. The suction field under the slab also seemed to decrease more rapidly with distance from the suction hole with the final system than it did during the test.

The difficulty with this situation is understanding why the pre-mitigation diagnostic test had indicated much better connectivity than shown by the systems. One possible explanation is that the sub-slab properties change rapidly from place to place; since the pre-mitigation vacuum cleaner suction hole was never in exactly the same location as the mitigation pipe, the differences could be simply a reflection of the fill variability. Another possible explanation is that there could be seasonal changes in the soil moisture which in turn affects the fill moisture and permeability. Finally, the high suctions produced by the test vacuum cleaner might change the fill properties during the pre-mitigation communication test. Further work is planned on this topic. It is apparent that there are aspects of the sub-slab fill condition that pre-mitigation diagnostic testing do not fully reveal.

Another factor of note was the variability of the radon concentrations in House 7. The pre-mitigation concentration of 10.9 pCi/L reported in Table IV is the average of two separate Pylon measurements covering a total of 164 hours (see Figures 07-1 and 07-2 in Appendix C). The radon levels averaged 8.2 pCi/L during the first 48 hours; 19.8 pCi/L over the next 22 hours; 4.6 pCi/L over the next 48 hours; and 15.8 pCi/L over the last 46 hours. Variation of radon concentrations by a factor of 4 is not unusual; however, the subdivision into four such distinct periods has not commonly been observed elsewhere. In a similar manner, the post-mitigation result of 2.6 pCi/L is the average of 91 hours of Pylon monitoring, in which the level averaged 4.4 pCi/L for the first 24 hours, and 1.9 pCi/L for the remaining 67 hours (see Figure 07-3).

The system fan was temporarily reversed in Houses 7 and 43 as a test of the effect of soil ventilation with the fan in pressure. The results of this sub-slab pressurization testing are presented in Table V. As shown in the table, the performance in pressure was always inferior to that obtained at the same fan speed with the system in suction.

The post-mitigation result shown in Table V for House 7 in suction differs slightly from that given in Table IV. The 2.2 pCi/L in Table V represents the average of 93 hours of Pylon testing

Table V. PRESSURIZATION VS. SUCTION WITH SSV - BASEMENT HOUSES

House No.	Average Radon Concentration (pCi/L) Pre-Mitigation	Post-Mitigation		% Reduction	
		Suction	Pressure	Suction	Pressure
7	10.9	2.2	5.8	80	47
43	14.3	0.5	5.3	96	63

with the fan operating at half speed in suction, just before the run (at half speed) in pressure. See Figures 07-4 and 07-5 in Appendix C. The 2.2 pCi/L is used here because it gives the best back-to-back comparison of suction versus pressure. The post-mitigation value of 2.6 pCi/L given for House 7 in Table IV represents the average from an earlier 91-hour Pylon run with the fan in suction at high speed. Since the fan was left at high speed in the permanent system, the value of 2.6 pCi/L was felt to be the appropriate value to include in Table IV.

SECTION 7

EXPERIENCE WITH SUMP VENTILATION IN BASEMENT HOUSES (OBJECTIVE 1B)

7.1 GENERAL

Soil ventilation via the sump and soil drains is a mitigation technique which has been proven effective in studies elsewhere. As with Objective 1A, the primary intent of Objective 1B was to determine how the house construction and geological characteristics of the Dayton area might influence the design and operating conditions needed for successful sump ventilation systems in "pure" basement houses.

The effectiveness of sump ventilation depends upon the extent and location of the drain-tile network draining into the sump. Best results are achieved when there is a complete loop or extensive network of drain-tiles, thus facilitating the distribution of the suction created in the sump by the mitigation system. Location of the drain-tiles is important; when they are near the wall/floor joint wall, as is commonly the case, they distribute the suction near to what is almost always an important soil gas entry route. The effectiveness also depends upon the ability of suction on the sump/drain-tiles to create a suction field underneath the entire slab.

Two houses (Houses 4 and 32) were selected to test Objective 1B. Both houses were believed to have an extensive drain-tile loop draining into the sump. In the case of House 32, the homeowner had construction drawings indicating that complete drain-tile loops were to be placed both inside and outside the footings. Two tiles were visible entering the sump. For House 4, the owner did not have any drawings for the drain-tiles, but a clay pipe entered the sump, suggesting that exterior tiles were present. In House 4, in addition to the clay pipe, there was also an 12.5 cm diameter opening closes with tar-paper through the side of the sump. The sub-slab fill was visible through openings in the paper. The washing machine and the central air conditioning condensate also drained into the sump in this house.

The pre-mitigation diagnostic tests conducted in houses with sumps included measurement of sub-slab communication using the industrial vacuum cleaner (capable of drawing up to 10 kPa, or 40 " H_2O) suction. In House 4, with the vacuum drawing 2.5 kPa (10 " H_2O) at the suction hole through the slab, a sub-slab suction of 12 Pa (0.05 " H_2O) was measured at a test hole drilled 8 m (24 ft) away from the suction hole; this result indicates very good sub-slab communication. In contrast, at House 32, a vacuum of 250 to 500 Pa at the suction hole produced no noticeable sub-slab depressurization (not even a downward flow of smoke) at a test hole about 3 m (10 ft) away, even though downward smoke flow was noticed at some segments of the wall/floor joint. Thus, the communication under House 32 was uncertain, despite house drawings which called for 4 inches of crushed rock under the slab.

7.2 SYSTEM DESIGN AND INSTALLATION

To permit testing of the sump ventilation system before committing to the final installation, a temporary exhaust fan installation that required minimum work was initially made in Houses 4 and 32. A temporary cover (plywood at House 4, a plastic garbage can at House 32) was placed over the sump and sealed to the concrete with expanding urethane foam. A 4-inch pipe was inserted through the cover. A basement window was removed, and a fitted plywood panel with a 4-to-6 inch adaptor was placed in the opening. The fan was attached on outside to the 6-inch end of the adaptor with set-screws so that it could be physically reversed to test the system in pressure. The exhaust pipe was attached to the 4-inch end of the adaptor on the inside.

At both Houses 4 and 32, the final installations involved a sump cover consisting of 1/2-inch thick lucite cut in a circular pattern to just fit into the sump opening. In both houses, the sump lining formed a rim just below the top surface of the concrete slab. This rim offered a convenient support upon which to seal the lucite cover. For further structural support, "bars" of lucite were placed across the cover, and bolted into the slab at several points around the perimeter of the cover. With the perimeter of the cover sealed around the perimeter to the rim, the surface of the lucite was slightly lower than the surface of the slab; a trapped drain was installed in the cover, so that if any water flowed to the sump from on top of the slab, the water would naturally flow onto the cover and down into the sump through the trap. Openings were made in the lucite cover for the sump-pump water discharge line and the electrical cord to the submersible sump pump, as well as for the 4-inch diameter PVC mitigation suction pipe. Mortite or foam tape were used to fill any gaps around the penetrations through the cover. In House 4, a drain pipe from the clothes washer also penetrated the cover. The 4-inch suction pipe from the sump penetrated the basement wall above grade into the back yard. A wall-mounted G-2 fan (a version of the Kanalflakt T-2 fan) was then connected to the pipe and screwed to the exterior the basement wall above-grade, discharging horizontally just above grade level.

In House 32, the testing also included extensive efforts to close the wall/floor joint and other slab openings (under Objective 5). The results of this closure effort are further discussed in Section 11.

7.3 PERFORMANCE

The results obtained with sump ventilation in these two houses are summarized in Table VI, with further details presented in Appendix C. As before, the pre- and post-mitigation radon levels presented in Table VI are short-term (roughly 96-hour) Pylon results, chosen to present the most

Table VI. PYLON RESULTS - SUMP SUCTION IN BASEMENT HOUSES

	Radon Concentrations in Basement (pCi/L)				
House	System Off		System On		% Reduction
No.	Range	Mean	Range	Mean	in Mean
4	1-247	35.8	0- 2	0.5	99
32	12- 37	27.0	0- 2	1.2	96

Note: Radon in Bq/m^3 = 37 x value in pCi/L meaningful back-to-back system on/off comparison. All these results are with the system operating in suction.

The performance of the systems at houses 4 and 32 was very good, reducing the concentrations to below 40 Bq/m^3 (1 pCi/L). This result is consistent with sump suction results elsewhere in cases where the drain tile loop was reasonably complete and where sub-slab communication was good. In contrast to the sub-slab systems in Section 6, where system flows were as low as 2 to 10 L/sec (4 to 22 cfm), at suctions of 150 to 350 Pa, both of the sump ventilation systems drew 60 to 66 L/s (125 to 140 cfm) with suctions of 100 Pa (0.4 " H_2O). The higher flows, could be due to the larger draw area provided by the tiles, or to relatively higher permeability in the soil around the two sump houses. At House 32, when the wall/floor joint was closed in connection with Objective 5, thus preventing any airflow from the house, the airflow from the sump suction system was reduced by only 20%. This result shows that much of the air appearing in the sump suction exhaust is air drawn through the soil, supporting the thesis that the effective soil permeability at that house is high.

The sump suction fan was reversed in both Houses 4 and 32, as a test of the effect of sump ventilation by pressure. These results are shown in Table VII. The performance in pressure was always inferior to that obtained at the same fan speed with the system in suction.

Table VII. PRESSURIZATION VERSUS SUCTION WITH SUMP VENTILATION

House No.	Average Radon Concentration (pCi/L) Pre-Mitigation	Post-Mitigation Suction	Post-Mitigation Pressure	% Reduction Suction	% Reduction Pressure
4	35.8	0.5	1.7	99	95
32	27.0	1.3	2.9	95	89

SECTION 8

EXPERIENCE WITH SSV IN BASEMENT PLUS SLAB-ON-GRADE HOUSES (OBJECTIVE 2)

8.1 GENERAL

Previous experience with sub-slab ventilation in basement houses having adjoining slab-on-grade wings, is that sometimes it is necessary to insert ventilation pipes directly under the adjoining slab, as well as under the basement slab. If pipes into the basement slab alone were sufficient this would simplify system design and installation, and would reduce the visual impact in the house. Since the basement slab is the lowest point in the house, there is some basis for hoping that, an SSV system in the basement alone might achieve "site ventilation" that would divert soil gas from entering at openings in the adjoining slab as well as the basement. Suction on the lowest geological strata beneath the house might spread horizontally underneath the entire site, so that direct suction beneath the adjoining slab would not be needed.

Two houses (Houses 11 and 21) were selected to address this objective. House 11 was a traditional four-level side-split design, with the basement slab and the adjoining slab on grade having approximately equal floor areas. The foundation walls were of poured concrete. House 21 was somewhat atypical, in that it had originally been a pure slab-on-grade house (with sub-slab heating ducts), to which the owner had converted the attached garage into a family room, and added a small basement/tornado shelter beneath that room. This house was not a split-level, in that the floor of the family room addition was on the same level as the original slab-on-grade. The foundation walls of the basement addition were block filled with concrete; the foundation of the original slab-on-grade was poured concrete. The basement side-walls are set in from the original poured concrete garage foundation walls by a distance of 70 cm (about 2 ft). The soil in the gap between the top of the basement wall and the adjoining foundation is covered by a 10 cm thick poured concrete layer forming a ledge 70 cm wide. Also of particular interest in House 21 is that the original slab-on-grade foundation was dug in the surface clay soil, but that the owner broke through the clay layer into a layer of gravel beneath the clay when he excavated the basement. This house also had a "sump hole" in one corner of the basement, with the bottom of the sump being the underlying gravel; no drain tiles were present.

Pre-mitigation sub-slab communication tests showed good communication under the basement slabs of both of these houses. Using the 10 kPa industrial vacuum cleaner to draw suction under the basement slab, sub-slab suctions measured under the basement slab at test holes 3 to 6 m (10 to 20 ft) from the suction point were 10 to 50% of the suctions measured 0.3 m (1 ft) from the suction point. Thus, it appeared that treatment of the basement slab would not be a problem. However, the diagnostic tests could not show any clear communication between the adjoining slab and the basement slab. Coarse construction aggregate could be seen under the basement slab at House 11, and natural gravel under the basement slab at House 21.

8.2 SYSTEM DESIGN AND INSTALLATION

In House 21 addition of the basement, which penetrated the clay layer into the underlying (presumably permeable) gravel layer, probably had increased the entry of soil gas into the house. This was supported by the fact that the average radon concentrations in the basement of this house were 3,650 Bq/m^3, (98.6 pCi/L) as measured by alpha-track detectors were the highest of those measured in this project. Accordingly, the first mitigation step attempted in this house was sealing the sump hole. The bottom of the sump was closed using expanding urethane foam; as an added sealant, condensed water from the dehumidifier (which drained into the hole) half filled the sump on top of the foam. Despite this unambiguous seal, radon concentrations in the basement were not noticeably affected, indicating that there were many other routes of radon entry besides the sump. (See Figures 21-2 and 21-3 in Appendix C.) The foam was cut out of the sump hole so that the hole could be used in the subsequent SSV testing.

Initially, the SSV installations in both houses involved one suction pipe in the basement. In House 11, this pipe was at the end of the basement beside the stem wall with the adjoining slab on grade, not quite in the middle of the length of stem wall. In this house a 12.5-cm hole was cored through the slab for the suction pipe and the underlying aggregate was removed, in a similar manner to the procedure described in Section 6 for Objective 1A. In House 21 the sump hole was used; this hole was in one corner of the basement, on the opposite side of the basement from the wall adjoining the slab on grade. A lucite cover was sealed over the sump hole, and the suction pipe inserted through the lucite, analogous to the approach described in Section 7 for Objective 1B. However, since there are no drain tiles entering this sump, this installation is not a sump/drain-tile suction system; rather, it is a SSV system with the slab opening and sub-slab excavation conveniently ready-made.

These one-point basement SSV systems achieved significant radon reductions in these houses, both in the basement rooms and in the rooms on the adjoining slab-on-grade. However, levels in both basements were still approximately 150 Bq/m^3 (4 pCi/L) — higher than might have been anticipated, in view of the excellent communication measured prior to mitigation. Sub-slab suction-field extension measurements with the mitigation systems operating confirmed that suction did not extend as well as expected in House 11, where a second suction pipe was installed on the opposite end of the basement from the first pipe in the area where the suction field was the weakest. Measurements at House 21 confirmed that the suction-field extended beneath the entire basement floor slab.

In both houses the systems were connected to Kanalflakt T-2 fans. In House 11 the two suction pipes were connected together and a 4-inch diameter pipe exited the basement through the concrete foundation wall below the exterior brick veneer. The in-line fan was mounted outdoors on this pipe with a 4-to-6-inch adapter, and discharged horizontally at grade level in the back yard. In House 21 the piping was run up through the basement stairwell into the attic. The fan was mounted on the pipe in the attic, discharging through an ornamental roof-top cupola.

8.3 PERFORMANCE

The initial one-pipe SSV installation in House 11 reduced concentrations from an average of 900 Bq/m^3 (24.4 pCi/L) in the basement just before activation of the system, to an average of 130 Bq/m^3 (3.5 pCi/L) over 174 hours of post-mitigation Pylon measurements. (For the derivation of these radon values, see the notes below the Pylon monitoring summary table for House 11 in Appendix C). Concentrations on the adjoining slab were reduced from an average of 610 Bq/m^3 (16.6 pCi/L) to 90 Bq/m^3 (2.4 pCi/L). While these post-mitigation concentrations met the previous EPA guideline of 150 Bq/m^3, they were higher than had been anticipated in the basement, in view of the excellent sub-slab communication measured during the tests. Suction field extension measurements showed that sub-slab depressurization with the system operating was generally in the range of 5 to 32 Pa (0.02 to 0.13 " H_2O), although the test hole in the diagonally-opposite corner most remote from the suction point and about 10 m (30 ft) away indicated a depressurization of only 2 Pa. Thus, a second suction pipe was installed near the basement wall at the other end of the basement from the first pipe. With this second pipe, sub-slab depressurization was 27 Pa (0.11 " H_2O) or greater at all of the test holes.

The results of the SSV testing in these houses — with the two-point system in House 11 and the one-point system in House 21 — are presented in Table VIII. Again, the results shown are the Pylon measurements felt to give the best back-to-back, system on/off comparison. The measurements in House 21 were completed in mid-March, when the weather was still cold. The final measurements on the two-point system in House 11 (with the fan either on and off) were not completed until mid-April, at which time the weather was milder.

Table VIII. PYLON RESULTS - SUB-SLAB SUCTION IN THE BASEMENT OF BASEMENT-PLUS-SLAB-ON-GRADE HOUSES

	Mean Performance - Basement			Mean Performance - SOG		
House No.	pCi/L Before	pCi/L After	% Reduction	pCi/L Before	pCi/L After	Reduction
11	9.2	1.2	87	5.1	1.1	78
21	125.1	4.0	97	12.6	0.9	93

Note: Radon in Bq/m^3 = 37 x value in pCi/L

As shown in the table, radon concentrations in the living area were in both cases reduced to about 1 pCi/L, while basement concentrations were reduced to 4 pCi/L or less. Addition of the second suction point in House 11 had a significant effect, compared to the levels with just one point, but part of this effect may be due to milder weather and less challenging conditions during the measurements.

It is not possible to determine unambiguously from the data why radon concentrations were reduced upstairs. Perhaps the desired "site ventilation" was indeed occurring, with the basement suction field extending in some manner to directly treat the entry routes associated with the adjoining slab-on-grade. However, pressure measurement equipment could not detect a depressurization under the adjoining slab caused by the basement SSV system. Thus it is possible that the mitigation systems were treating the basement alone, and the reductions upstairs resulted simply because the basement was the major entry route. In this latter case, the system would simply be reducing the migration of radon from the basement to the upstairs. Some support for this view is given by the fact that the ratio of the basement to living area concentrations was similar to the inverse ratio of the basement and living area volumes, as would be expected if the supply were entirely via the basement.

Both houses had poured concrete (or concrete-filled block) foundation walls, so that the radon supply through the walls was not a factor here. If the walls had been hollow block the wall between the basement and the adjoining slab could provide a channel for air leakage into the ground which could interrupt the suction field developed in the soil, and so the effect of the SSV system would be confined to the basement.

It is curious why the basement in House 21 is still as high as 4.0 pCi/L. Sub-slab depressurization measurements indicate that the SSV system is creating a depressurization of 10 Pa (0.04 " H_2O) even at the test hole most remote from the suction pipe, about 6 m (20 ft) away, hence there cannot be any radon entry through the floor slab. Since the walls are filled with concrete, there should not be much radon entry through the walls. Adding to the mystery is that the flows in that SSV system were unusually low (2 to 6 L/sec, or 4 to 13 cfm). Since it was known that the basement was underlain by natural gravel, which would presumably be reasonably permeable, these low flows are all the more curious. One thesis is that the flow resistance in the gravel prevents the sub-slab suction-field from extending beneath the footing, and so there is no significant airflow down through the soil beneath the 70 cm wide concrete ledge between the basement wall and the solid concrete house and garage foundation-walls. Thus, radon might still be entering the basement from the soil beneath the paved ledge.

The system fan was reversed in House 11 during the time that the one-point SSV system was in place, as a test of the effect of sub-slab pressurization versus suction. The performance under pressure was inferior to that obtained at the same fan speed with the system in suction. Concentrations in the basement, which averaged 24.4 pCi/L over 43 hours without the fan operating (just before the suction vs. pressure testing), averaged 3.5 pCi/L over 174 hours with the fan operating at low speed in suction (for a reduction of 85%), but averaged 9.1 pCi/L over 68 hours with the fan in pressure at low speed (for a reduction of only 61%).

SECTION 9

EXPERIENCE WITH SLAB-ON-GRADE HOUSES HAVING SUB-SLAB DUCTS (OBJECTIVE 3)

9.1 GENERAL

There is little experience with radon mitigation systems in slab-on-grade houses. As an added complication all four of the slab-on-grade houses tested in this study (Houses 1, 15, 31 and 47) had forced-air heating supply ducts beneath the slab, radiating from a centrally-located down-draft furnace to register boxes located around the perimeter of the houses. Under these circumstances it would be anticipated that a suction field created by a sub-slab suction system would not extend beyond the segment bounded by the heating ducts, which could provide a supply of indoor air large enough to neutralize the suction since the joints between the duct sections are not air-tight. The ducts are sandwiched between the clay soil below, and the concrete floor-slab above. This further reduces the likelihood that a suction field could extend past a duct.

Initial diagnostic testing on the four houses confirmed the anticipated poor sub-slab communication, although the sub-slab fill appeared to be pea gravel. For example, in House 1, suction on a hole through the slab (using the 10 kPa industrial vacuum cleaner) created a sub-slab depressurization of 6 Pa (0.02" H_2O) at a test hole 2.5 m (8 ft) away on the near side of a heating duct, but no depressurization could be detected at a second test hole on the far side of the duct.

On this basis, the initial conclusion was that sub-slab suction would probably not be a viable approach for these houses. The radial sub-slab ducts would divide the sub-slab region into eight or more isolated triangular zones, and it appeared that suction on one zone would not extend to the others. Placing a suction pipe into each zone would be difficult to implement. To add to the problem, the sub-slab space was pressurized by leakage from the ducts, so an exhaust system would also have to overcome this.

Therefore, the initial testing on the four slab-on-grade houses addressed options other than SSV by additional systems. The initial approach was to pressurize the sub-slab region by continuous operation of the central furnace fan. Since the sub-slab ducts were warm-air supply ducts, continuous operation of the central fan was expected to pressurize the sub-slab by blowing house air into the sub-slab fill through the leaky joints between duct sections, and between the ducts and the furnace plenum. The pressures created in the ducts are about 20 Pa (0.08" H_2O); for this approach to be effective, this pressure must be distributed effectively to create a "pressure bubble" in the soil under the house, and resulting airflows must be sufficient to divert and dilute the soil gas that would otherwise be drawn into the house. Continuous operation of the furnace fan would also have the effect of preventing the ducts and registers from being an entry route for soil gas, as the whole distribution system was under pressure.

A second approach tested was to close major accessible openings through the slab. In practice this amounted to closure of the opening under the bathtub where the plumbing comes up through the slab, using expanding urethane foam. It was recognized that this step would likely be insufficient to reduce the radon concentration greatly, in view of the other inaccessible slab openings left unclosed, such as the wall/floor joint. However, it was felt to be important to see what effect closure of the bath plumbing opening would have, since this is the type of action that homeowners could easily implement themselves.

Only after these other measures were tested was sub-slab ventilation attempted.

Houses 15, 31 and 47 each were of moderate size (about 90 m^2, or 1,000 ft^2), and had poured concrete foundations. House 1 was about twice as large (185 m^2, or 2,000 ft^2), and had a block foundation.

9.2 PERFORMANCE OF CENTRAL FAN OPERATION AND SLAB CLOSURE

The radon reductions produced in the four slab-on-grade houses by continuous operation of the central furnace fan, and by closing the slab opening under the bathtub are summarized in Table IX.

Table IX. PYLON RESULTS - FURNACE FAN OPERATION AND SLAB CLOSURE IN SLAB-ON-GRADE HOUSES

House No.	Mean pCi/L Before	Mean Performance After					
		Fan Operation		Slab Closure		Fan + Closure	
		pCi/L	% Red.	pCi/L	% Red.	pCi/L	% Red.
1	20.2	21.2	(-5)	--	--	--	--
15	17.9	4.6	74	8.8	51	1.1	94
31	14.7	12.8	13	9.8	33	10.4	29
47	29.6	14.5	51	20.4	31	9.7	67

Notes: House 1 did not have an opening under the bathtub for closure.
Radon in Bq/m^3 = 37 x value in pCi/L.

As shown in the table, continuous operation of the furnace fan resulted in a moderate reduction in Houses 15 and 47, and essentially no reduction in Houses 1 and 31. Sub-slab pressure field measurements confirmed that fan operation increased the sub-slab pressures by several pascal at all of the test holes. The small reductions achieved indicate that this pressurization was insufficient to keep radon out of the sub-slab space. Perhaps the flow of air created under the slab was not sufficient to sweep the radon away, or perhaps not all of the sub-slab area was being adequately pressurized/ventilated. In House 1 — the only one of the four slab houses to have a hollow block foundation — radon could also have still been entering via the block cores, although the top of the block foundation is capped with an inverted U-block.

Closing the opening under the bathtub gave some apparent reduction in Houses 15, 31, and 47. House 1 had no opening under the tub.

For the two houses where operation of the central furnace fan had an effect prior to closing the bathtub opening, closure of this opening improved the radon reduction effectiveness of fan operation.

Only in the case of House 15 did the above steps reduce radon levels below 4 pCi/L. Thus, additional mitigation methods were clearly required for the other houses.

9.3 SSV SYSTEM DESIGN AND INSTALLATION

Prior to attempting more complex measures in the slab-on-grade houses, it was decided to test a simple sub-slab ventilation approach, even though the diagnostic results as well as intuition indicated that simple sub-slab suction systems should not be effective.

To minimize the work needed to test an approach that was expected to produce only small reductions in radon concentration, the initial work was carried out from outside the house. In Houses 1, 15 and 47, one 8-cm (3-inch) diameter hole was cored horizontally through the solid foundation wall from outside the house, below the level of the underside of the floor slab. This hole was placed either at one end of the house (Houses 15 and 47), or near the middle of the rear of the house (House 1), and entered into one of the larger sub-slab zones bounded by the heating ducts.

For Houses 15 and 47, with poured concrete foundations, the hole cored from outdoors went all the way through the wall into the sub-slab fill. In House 1, with a block foundation, the 8-cm hole was initially cored only through the outer face of the block; in this configuration, the fan was drawing suction on the block cores. The top block (at the level of the slab) appeared to be an inverted U-block, capping the top of the block wall. Following testing of this initial configuration, two 4-cm (1.5-inch) holes were drilled through the inner face of the block, opposite the 8-cm hole in the outer face, in an effort to improve the extension of the suction under the slab. A plastic flange was sealed to the exterior foundation wall over the cored hole, and a portable T-2 fan mounted in a box was connected to the flange by a short length of flexible drier vent hose. In the final installations, the fan was mounted on a piece of marine-grade plywood and simply screwed to the side of the house over the hole.

In House 31, two temporary installations were utilized. The first used a hole cored through the solid concrete foundation wall at the bedroom end of the house, and the second used a pipe inside the house, inserted into the sub-slab fill through the foam which had been used to close the slab opening under the bathtub. The bathtub was located at the rear of the house, near the middle. The sub-slab pipe was connected to a fan mounted in a box (for portability), exhausting through a rear door. In all cases, the fan was a Kanalflakt T-2, capable of drawing 127 L/sec (270 cfm) at zero static pressure, and capable of 350 Pa (1.4 " H_2O) suction at zero flow.

9.4 PERFORMANCE OF SSV SYSTEMS

The results from operation of these minimal sub-slab suction systems are summarized in Table X. The results shown for House 1 are for the configuration after the two 4-cm holes were drilled through the inner face of the block foundation. These measurements were obtained in late April; for the other three houses, the measurements were completed by mid-March, when the weather was colder. For all houses, the results in the table are for the case where the central furnace fan is cycling normally. Additional information on all of these houses is presented in Appendix C.

As shown in the table, the simple SSV system reduced the radon concentrations in all four houses to the vicinity of 1 pCi/L, with reductions greater than 90% in all cases. It is not understood why these systems were so effective. Sub-slab suction field extension measurements with the systems

Table X. PYLON RESULTS - SUB-SLAB SUCTION IN SLAB-ON-GRADE HOUSES

House No.	Radon Concentrations System Off Range	Radon Concentrations System Off Mean	Radon Concentrations System On Range	Radon Concentrations System On Mean	% Reduction in Mean
1	14-32	20.2	0- 3	1.3	94
15	6-42	17.9	0- 1	0.5	97
31	7-27	14.7	0- 2	0.8	95
47	20-39	29.6	0- 2	0.9	97

Note: Radon in Bq/m^3 = 37 x value in pCi/L

operating showed no measurable suction being created under the slab by the systems in regions remote from the suction point, consistent with the pre-installation diagnostics.

In the three houses with poured concrete foundations system flows were 20 to 32 L/sec (43 to 69 cfm), and the suctions developed at the fan were about 250 Pa (1" H_2O), indicating that the system was not being overwhelmed by air leaking into the sub-slab region through the heating ducts. In House 1, with the block foundation, flows were somewhat higher (40 L/sec, or 85 cfm). The higher flows at House 1 probably reflect leakage of air into the system via openings in the mortar between blocks.

In all four houses, the radon measurements with the SSV system operating were repeated with and without the central furnace fan operating continuously. When the furnace fan was not operating continuously, it was cycling normally. Since the furnace fan would tend to pressurize the sub-slab region, it would presumably be working against the SSV system, which is trying to depressurize the sub-slab. In two of the houses (Houses 15 and 47), continuous operation of the furnace fan (as distinguished from normal cycling) had no apparent effect on the indoor radon concentrations (i.e., the levels shown in Table X remained basically unchanged when the furnace fan was turned onto continuous operation). In House 31, furnace fan operation increased radon concentrations somewhat, to an average of 115 Bq/m^3 (3.1 pCi/L), compared to the level of 30 Bq/m^3 (0.8 pCi/L) when the fan was cycling.

In House 1, continuous operation of the furnace fan increased indoor levels to 390 Bq/m^3 (10.6 pCi/L) in late April, compared to the level of 48 Bq/m^3 (1.3 pCi/L) with the furnace cycling. This increase suggests that the system was marginal, and susceptible to being overwhelmed under some conditions. The fact that this increase was observed in mild weather and presumably less challenging conditions, compared to the other houses, exacerbates the concern.

Two possible reasons are immediately apparent why the results in House 1 were not as good as those seen in the other houses. One is size; since the House 1 slab is twice the square footage of the others, it could be that one SSV suction point is not able to effectively treat the entire slab, especially in view of the sub-slab ducts. The second is the block foundation; the hollow block cores could facilitate short-circuiting of air into the SSV system, thus reducing the suction under the slab.

Three of the slab-on-grade houses were tested with the SSV system fan temporarily reversed to pressurize the sub-slab space. As shown in Table XI, in all cases the system was more effective with the fan in suction. As before, the post-mitigation data with the system in pressure shown in Table XI can differ in some cases from the values in Table X. The post-mitigation suction data in Table XI are from the test most comparable to that with the system in pressure; in some cases, the test might have been closer in time, or with a different fan speed, than that presented in Table X.

Table XI. PRESSURIZATION VS. SUCTION WITH SSV - SLAB-ON-GRADE HOUSES

House No.	Average Radon Concentration (pCi/L) Pre-Mitigation	Post-Mitigation Suction	Post-Mitigation Pressure	% Reduction Suction	% Reduction Pressure
15	17.9	0.4	1.8	98	90
31	14.7	0.4	4.2	97	71
47	29.6	2.9	16.0	90	46

SECTION 10

EXPERIENCE WITH CRAWLSPACE VENTILATION (OBJECTIVE 4)

10.1 GENERAL

There is limited experience with radon mitigation systems in crawlspace houses. Accordingly, the testing on the four crawlspace houses (Houses 22, 24, 28 and 33) began with the simplest approaches, namely, testing two types of crawlspace ventilation.

The first type of crawlspace ventilation tested here was natural ventilation, i.e., simply opening the existing vents in the crawlspace foundation wall. Natural crawlspace ventilation would work largely by diluting the radon in the crawlspace, so that the crawlspace air entering the living area would import less radon. Natural ventilation might also reduce the driving force drawing radon up out of the soil, in that the upward gas flows resulting from the thermal stack effect in cold weather would consist to a greater extent of outdoor air drawn in through the vents, and to a lesser extent of soil gas. The houses in this study had between 5 to 7 standard-size foundation vents. The total open area of the vents in these northern houses is less than in southern houses, where codes commonly call for a minimum amount of vent area per unit floor area in the crawlspace for moisture control purposes. Thus, it was of interest to determine whether the existing vent areas in these houses were sufficient to provide enough ventilation to give significant radon reductions. It is recognized that implementation of year-round natural ventilation in northern crawlspaces would require measures to avoid water-line freezing and undue heat loss from the living area during the winter, such as insulation of water pipes and the living area floor. The question being addressed in this study is whether natural ventilation can provide sufficient radon reductions to make it worthwhile to consider these insulation steps.

The second type of crawlspace ventilation tested was forced ventilation, with the ventilation fan oriented to draw air out of the crawlspace. If the crawlspace is sufficiently isolated from the outdoors and from the living area, this forced exhaust will depressurize the crawlspace relative to the living area. This approach would be expected to work not so much by diluting the radon in the crawlspace, but by reversing the air flows between the crawlspace and the living area. If successful, clean house air will flow into the crawlspace, rather than radon-containing crawlspace air flowing into the living area. Since much of the air exhausted by the fan will consist of heated house air drawn down into the crawlspace, forced exhaust avoids the threat of water pipe freezing in the winter. However, by the same token, there will be an energy penalty in exhausting conditioned house air. In the temporary installations tested in this study, the ventilation fan was a Kanalflakt T-2 mounted outside the crawlspace drawing air through one of the foundation vents or the crawlspace entry. To increase crawlspace depressurization, the other foundation vents were closed with the existing dampers during forced exhaust testing. However, no additional sealing of the crawlspace foundation wall or of the subfloor beneath the living space was attempted.

Other mitigation measures to be tested in Phase 2 of the Dayton project are: forced ventilation of the crawlspace with the fan reversed to blow outdoor air into the crawlspace, to pressurize the area; "site ventilation", drawing suction on pipes embedded in bare soil in an effort to treat the entire site; and "sub-liner" ventilation, with suction being drawn on perforated pipes placed underneath plastic sheeting placed over the crawlspace soil. A key parameter in the sub-liner ventilation testing will be the degree of sealing needed at the junction between the plastic and the crawlspace foundation wall, and where plastic sheets are joined together.

10.2 PERFORMANCE

The results with natural ventilation are presented in Table XII. The results with forced crawlspace exhaust are shown in Table XIII.

Natural ventilation gave radon reductions of 46 to 83% in the living area, and usually greater reductions in the crawlspace. Two of the houses were reduced below 4 pCi/L in the living area by this technique. The radon concentrations in the crawlspace were generally reduced by a greater percentage than the concentrations in the living area; whereas the crawlspace levels had been roughly twice the living area levels prior to natural ventilation, the two concentrations generally became more nearly equal with ventilation. That the living area and crawlspace concentrations were not reduced by the same percentage suggests that natural ventilation increased the flow of crawlspace air into the house.

Table XII. PYLON RESULTS - NATURAL CRAWLSPACE VENTILATION

	Foundation Vents Closed (Pre-Mitigation)		Foundation Vents Open (Natural Ventilation)			
	Mean Radon Level (pCi/L)		Mean Radon Level (pCi/L)		% Reduction	
House No.	Living Area	Crawlspace	Living Area	Crawlspace	Living	Crawl
22	17.0	27.3	9.1	10.7	46	61
24	15.9	32.5	6.8	15.1	57	54
28	5.0	31.1	2.7	4.2	46	86
33	16.6	41.3	2.9	3.8	83	91

Notes: House 22 had 6 foundation vents; House 24, 5 vents; House 28, 7 vents; House 33, 5 vents.

Radon in Bq/m^3 = 37 x value in pCi/L.

Forced crawlspace exhaust in all cases gave greater radon reductions in the living area than did natural ventilation, although two of the houses were still above 4 pCi/L in the living area. However, radon reductions in the crawlspace with forced exhaust are much less than with natural ventilation. Thus, the crawlspace depressurization mechanism must be coming into play, reversing (or at least reducing) the flow of crawlspace air into the house. By depressurizing the crawlspace, the forced exhaust draws more soil gas into the crawlspace, largely offsetting the effect of increased ventilation. The potential of the crawlspace depressurization is demonstrated by the substantial decrease in living area radon concentrations while the crawlspace concentrations are decreased only moderately.

To assess the effects of natural and forced-air crawlspace ventilation on the ventilation rates in the crawlspace and the living area (and on the movement of air between these two zones), perfluorocarbon tracer (PFT) measurements were made in these houses at the same time as the radon measurements. The PFT measurements are discussed below. The results of the tracer measurements

Table XIII. PYLON RESULTS - FORCED CRAWL SPACE EXHAUST

House No.	Foundation Vents Closed (Pre-Mitigation) Mean Radon Level (pCi/L) Living Area	Crawl Space	Forced-Air Exhaust Mean Radon Level (pCi/L) Living Area	Crawl Space	% Reduction Living	Crawl
22	17.0	27.3	4.4	23.8	74	13
24	15.9	32.5	4.8	17.6	70	46
28	5.0	31.1	0.8	26.1	84	16
33	16.6	41.3	1.3	21.9	92	47

Radon in Bq/m^3 = 37 x value in pCi/L.

generally agreed with the radon measurements, but were not as quantitative as had been hoped.

10.3 TRACER MEASUREMENTS OF VENTILATION RATES

10.3.1 Experimental Procedure

Perfluorocarbon tracers (PFT's) were used in the crawlspace houses to measure the changes in ventilation rate and internal circulation produced by the changes in the crawlspace ventilation. The PFT emitters are small metal tubes about 50 mm long mounted on push-pins. Three emitters were deployed in the living area, one at each end of the house, usually in the kitchen and bedroom, with the third near the center of the house, usually in the entrance hall-way. They were placed above head-level by pushing the pin into the top of the wooden casing that surrounds each door. The passive collector is a small glass tube 50 mm long containing a PFT adsorber. One of these was hung by a similar push-pin holder at the top of a door frame in a central location, often the dining area, at least 3 m from the nearest emitter. Two tubes containing a different emitter were placed in the crawlspace. The tubes were placed 1 to 2 m apart, with the pins pushed into the underside of the wooden floor joists at least 4 m from the crawlspace entrance. To ease retrieval, a single collector tube was hung from the underside of a joist 2 m from the crawlspace entrance, at least 4 m from the emitters.

Once the emitters were placed in a house, they were left undisturbed till the set of measurements was completed. New collectors were placed in the house each time the experimental conditions were changed, and left there for 3 to 4 days while the effect on the radon concentration was measured directly by a continuous radon monitor.

10.3.2 Discussion

The average ventilation rate in the living area, given by the ratio of measured average tracer concentration to calculated average source release rate, ranged from 0.2 to 0.5 ac/h as shown in Table XIV. The variations in ventilation rate with experimental conditions, and from house to house do not reflect directly the differences in house air-tightness, or the effect of the experiments. These measurements were made in March-April, and not only did the average air temperature rise over the period, but there were also a number of days when it was warm enough for the owner to open doors or windows for part of the day. This is known to have happened at Houses 28 and 33.

The correlation between the tracer measurements and the radon measurements for each experimental run is discussed in detail in the house Appendix, and only a general overview will be given here. Changes in the average living space concentration of tracer released in the crawlspace

Table XIV. LIVING AREA MEAN VENTILATION RATES

House #	Condition	m^3/h	ac/h
28	Vents closed	146	0.27
	" "	171	0.32
	Vents open	184	0.34
	Exhaust on	196	0.36
24	Vents closed	47	0.17
	Exhaust on	53	0.19
28	Vents closed	115	0.26
	Vents Open	70	0.16
	Exhaust on	68	0.15
33	Vents closed	104	0.35
	Vents open	173	0.58
	Exhaust on	148	0.49

were similar to, but not the same as the changes in the average living space radon concentration, suggesting that the tracer was not acting as a complete indicator of air movement from the crawlspace.

The tracer estimate of crawlspace ventilation rate and the measured forced exhaust flow from the crawlspace fan is shown in Table XV. The tracer estimate is lower in all four houses, suggesting a systematic error. A possible cause may be poor mixing of the tracer with the crawlspace air. The air in the living space is always well mixed, either by operation of heating or cooling systems, or thermally driven convection currents caused by window glass being cooler than the house air, or local heating caused by sunshine. In contrast, the forces that can generate mixing in the crawlspace are much smaller. The house floor is always warmer than the crawlspace air, and that is generally warmer than the soil of the crawlspace floor. Even when the vents are open, the cool air entering through the small openings rapidly looses its momentum, and tends to sink to the crawlspace floor due to its lower temperature. This is a situation where thermal stratification of the air is likely. The

Table XV. COMPARISON OF CRAWLSPACE VENTILATION ESTIMATES

House #	Fan exhaust rate m^3/h	Tracer exhaust rate m^3/h
22	170	103
24	180	48
28	140	30
33	181	55

emitters and detector were placed on the joists, and so if stratification did take place, the concentrations in the vicinity of the detector would be higher than the average concentration in the crawlspace. In addition to this effect, in three of the houses the temporary exhaust fan ventilated the crawlspace via the access opening. Both the emitters and detector were in that area, and so it is possible that the exit airflow patterns reduced the amount of tracer that mixed with the general crawlspace air, and increased the concentration measured by the detector.

10.3.3 Lessons Learned

The uncertainty in PFT measurements in crawlspace houses can be reduced by the following steps. First, whenever possible, the sets of measurements will be made over a long period in cold weather, so that there is no incentive for the owners to open the doors or windows. Measurements in 'shoulder' seasons where there are rapid changes in mean outdoor temperature with time will be avoided. Second, steps will be taken to produce uniform tracer concentrations in the area by using at least 3 emitters, widely separated from each other and from the detectors.

The tracer release rate is temperature dependent, a change of 5°C increasing the output by 25%. The outside air temperature varies widely from night to day, and the crawlspace temperatures may vary significantly. If high accuracy is needed, a recording temperature gauge will be used to measure the temperature in the crawlspace over the duration of a test, so that the average release rate can be estimated with higher accuracy if there are significant temperature swings. If the house occupants routinely set back the thermostat at night, a recording temperature gauge should also be used in the living area.

SECTION 11

EXPERIENCE WITH CAULKING AS A LOW-COST MITIGATION METHOD (OBJECTIVE 5)

11.1 GENERAL

Closure of soil gas entry routes is an intuitively appealing technique for reducing radon concentrations in houses. It is a passive technique, and is unobtrusive. It is especially attractive when homeowners can implement it themselves, thus avoiding labor costs. However, experience with entry route closure is that soil gas entry routes are numerous and often concealed behind finish and structural features. Moreover, even accessible entry routes can be difficult to seal effectively, and in a permanent manner (so that the openings do not reopen over time as the sealant ages and the house settles).

For the current study, two houses (Houses 32 and 49) were selected as being particularly amenable to a study of entry route closure. This meant: a) the house had a "pure" basement substructure, so that entry routes associated with the joint between slab-on-grade wings did not have to be addressed; b) the foundation walls were poured concrete, so that entry routes associated with hollow-block cores and porous block faces were avoided; c) the basements were totally unfinished, providing convenient access to all surfaces and entry routes; d) there were no obviously non-closable entry routes, such as block fireplace structures; and e) the slab and walls were not extensively cracked. The rationale for selecting such "textbook-case" houses was to make a proof-of-principle test of the type of sealing/ closure that homeowners might perform themselves in their spare time. If good radon reductions could be achieved in these "textbook" houses, this result would provide the incentive to consider closure in more complex cases. But if closure could not be made to do well even in simple cases, it would be all the more questionable whether this approach should be considered at all.

Two classes of entry routes were considered in this project: a) cracks and joints between poured concrete sections and b) sumps. There are three general types of cracks. The most important type of crack is the concrete butt-joint, which can be 0.5 to 5 mm (0.02 to 0.2 in.) wide; examples of butt-joints include the wall/floor joint, openings around utility pipes that penetrate the slab or walls, and expansion joints between different pours of concrete. The second most important type of crack is the slab crack (due to shrinkage and settling), which can vary continually in width from hairline to 5 mm, with irregular edges. The least important type of crack is the wall crack, which, like the slab cracks, can vary continually in width and have irregular edges. In this project, the closure effort focussed on: the sump in House 32; and butt-joint cracks (in particular, the wall/floor joint and openings around utility penetrations) in both houses. The houses were specifically selected as having limited shrinkage/settling cracks in the slab and walls; House 49 did have some such cracks, but these cracks were not closed in this project.

House 32, which had a sump, was selected for this objective because it met all the above criteria. However, the radon levels in the basement (1000 Bq/m^3, or 27.0 pCi/L) were sufficiently high such that it was not clear that closure alone would reduce the basement below 150 Bq/m^3.

This house was also being tested under Objective 1B (sump ventilation), and it was anticipated that, if closure did not provide sufficient reductions, sump ventilation would. Sump ventilation was tested both before and after the closure effort in this house. House 49 had no sump, and only slightly elevated radon levels (330 Bq/m^3 or 9 pCi/L) by the original charcoal measurement. It was thought that entry route closure by itself might give sufficient reduction in this house.

The major cost component of caulking is not of the cost of the materials, but in the labor needed to prepare the surfaces and to apply the caulk. The cost can only be low if the labor cost is low, i.e., provided by the homeowners in their spare time. Accordingly, only the materials and equipment that a homeowner could be expected to use were to used in these experiments. For example, preparation of those surfaces that would contact the caulk was limited to wire brushing the area either by hand or by electric drill.

11.2 INSTALLATION PROCEDURE

The primary effort focussed on caulking the wall/floor joints in the two houses. These joints ranged from 1 to 3 mm (1/32 to 1/8 in.) wide. Three different types of caulk were tried. The first choice was a "sagging" (but non-flowable) polyurethane caulk, which would be applied into the wall/floor joint corner. A second material that was investigated was a flowable urethane caulk, which had been tested and found to give a good seal with minimum surface preparation when poured into formed channels. It was hoped this flowable caulk would flow into intimate contact with both wall and floor surfaces and so minimize the need for surface preparation and accurate placement of the caulk bead. The final type of caulk tested was an industrial "pourable" solvent-based acrylic material with a higher viscosity than the flowable urethane, but a much lower viscosity than the sagging polyurethane.

Prior to applying the caulk, the surfaces of the slab and concrete wall near the joint were prepared by wire brushing to remove loose concrete and dirt. Following the wire brushing, the resulting dust was removed with a vacuum cleaner, then wet-sponging, then using a sticky material (such as the adhesive side of duct tape) in an effort to pick up the dust particles.

The flowable urethane caulk was tested first, on the basis that if it failed to seal any sections of the joint, the sagging polyurethane could be applied on top of the material. The flowable material did not perform well in this application. When it was applied to the wall/floor joint, the viscosity was so low that the material did not form anything of a bead; much of it simply flowed out onto the floor in a puddle. Some flowed down into the wall/floor joint, but not enough to form a continuous seal in the joint. The amount which actually flowed down into the 1 - 3 mm joint was so small that it would have been a very slow process to fill the joint to any depth by repeated applications. Up to three applications were made on some segments of the wall/floor joints in the two houses, and in no case did the caulk effectively fill the crack.

This flowable urethane caulk was also tested to see how effective it might be in closing wall cracks. A 12 mm hole was drilled 50 mm into the wall at the top of a crack, and the hole and face of the crack closed with a strip of tape. The hole filled with caulk, and topped up for an hour. When the tape was removed, it was seen that the caulk had travelled about 500 mm (about 20 in.) down the crack before it had finally set. At that rate it would need 3 or 4 sets of holes to completely close one wall crack by this method.

Openings around utility penetrations were closed using the flowable urethane caulk. For these isolated openings, a small dam of putty was built on the slab around the utility pipe to contain the caulk, so that it could not flow out onto the slab as it did when it was used on the wall/floor joint. Where the opening around the utility pipe was large, backer material was stuffed down the opening to reduce the amount of flowable caulk that would drain away into the sub-slab fill. The dam was kept filled with caulk for an hour, by which time caulk had ceased to drain into the opening. The putty did not adhere very well to the concrete floor surface, suggesting that a use of similar dam around the entire basement perimeter to fill the wall/floor joint with flowable caulk would not be practicable.

When the flowable urethane caulk proved to be ineffective in closing the wall/floor joint, a pourable acrylic caulk was tested on one segment of the wall/floor joint in House 32. This industrial material was not expected to be fully suitable for homeowner use, but had been suggested by the caulk supplier as an alternative to the flowable urethane — i.e., a material that did not flow as freely as the flowable caulk, but which would still settle into the crack more effectively than the sagging polyurethane caulk. Although the viscosity of the pourable acrylic was higher than that of the flowable urethane caulk, it was still not high enough to prevent it behaving in the same way as the urethane. In addition, it had such a strong and unpleasant odor that, even with local forced exhaust ventilation, only 6 m of wall/floor joint was treated with this material before it was decided that the product was completely unsuitable for indoor use.

The final type of caulk tested was the original choice, the sagging polyurethane caulk. This caulk was applied into the wall/floor corner, covering the joint. A number of application procedures were tested using over short lengths of the joint using different bead sizes and tooling procedures. The most of the caulk bead was applied without tooling. Radon measurements were made in the basements and over sections of caulk with the different application procedures. A larger bead of caulk was then applied over the initial bead, and tooled.

The second caulking produced no significant increase over the radon reduction achieved with the first caulking. In House 49, a primer was put down prior to the final bead of caulk, to improve adhesion to the concrete surface and to seal porosity in the concrete surface at the base of the foundation wall. Again, no clear improvement in radon reduction performance was apparent. In all cases, the caulk adhered well to the slab and wall surfaces.

The sump in House 32 was closed using a circular acrylic plastic cover, cut to fit into the sump opening, supported by a lip inside the sump liner. The plastic cover was "sealed" to the sump liner with Mortite putty around the perimeter where the cover rested on the lip. The joint between the sump liner and the concrete slab was caulked.

1.3 PERFORMANCE

The Pylon results obtained from these closure efforts are summarized in Table XVI. The post-mitigation results shown in the table reflect the final sealing effort — i.e., after the second bead of tooled polyurethane caulk around the wall/floor joint.

It would appear from the table that sealing had a moderate impact in House 32, perhaps because of the significance of the sump as a source in that house. The reductions in House 49 were less significant; considering the small difference in the radon concentrations, it is not clear that the sealing effort in that house had a real effect at all.

Even these inconclusive results must be viewed with caution, for they may overstate the effect of caulking. Because of the time required to perform the several caulking steps, there is an unavoidable time lag between the pre- and post-mitigation measurements. The pre-mitigation measurements were made in January through early March. (Referring to Appendix C, the pre-mitigation values in Table XVI were obtained from combined results of Figures 32-1, 32-2 and 32-3 for House 32, and from Figures 49-2 and 49-3 for House 49.) The post-mitigation measurements

Table XVI. PYLON RESULTS - SEALING IN BASEMENT HOUSES

House No.	Radon Concentrations in Basement (pCi/L) Before Sealing Range	Mean	After Sealing Range	Mean	% Reduction in Mean
32	12-37	27.0	3-18	10.2	62
49	3- 8	5.8	3- 7	4.4	24

Note: Radon in Bq/m^3 = 37 x value in pCi/L

were made in mid-April (Figures 32-8 and 32-9 for House 32, Figure 49-5 for House 49). Thus, milder weather, in addition to the sealing effort, could play a role in the reductions shown here.

The seal between the caulk and the concrete surfaces was tested by taping plastic sheets over segments of the caulked wall/floor joint, and over the sump in House 32, and measuring the radon concentrations under the sheets after 24 hours. Significantly elevated radon concentrations ranging from 1,500 to 21,500 Bq/m^3, (or 40 to 580 pCi/L) were measured under some of the plastic enclosures, indicating that radon was still entering the house despite the caulk over the wall/floor joint and the sump. A similar test after the second application of caulk found that the areas of high leakage were the same as in the first test. Since the caulk adhered well to the concrete, a possible explanation is that the soil gas and radon is bypassing the caulk bead, by moving through the porous surface layer of the concrete wall (the "laitance"). This was one of the factors which led to the use of a primer prior to the final caulking in House 49.

The radon reductions achieved with the large, tooled beads of caulk (as shown in Table XVI) were not any greater than those measured after the first caulking step. Early efforts to seal just the sump in House 32, prior to caulking the wall/floor joint, gave no apparent radon reduction in the basement (see Figure 32-2 in Appendix C).

These results are not an encouraging demonstration of the potential radon reductions achievable by the caulking efforts that might be implemented by homeowners.

SECTION 12

TERRESTRIAL RADIATION MEASUREMENTS AND LOCAL GEOLOGY

12.1 GAMMA MEASUREMENTS

12.1.1 Gamma Measurement Equipment

Gamma radiation measurements were made at mitigation houses and in the area generally with a 5-channel NaI scintillation meter which has been calibrated at the Department of Energy, Mines and Resources radioactive test pads in Ottawa. When the threshold is set so that the instrument responds only to gamma-rays above 400 keV, the count rate from each of the potassium, uranium, and thorium decay chains in a semi-infinite geometry is approximately proportional to the exposure rate from that nuclide. The meter is normally used set to that threshold, so that count-rate can be converted directly to exposure rate. The indicated exposure rate from cosmic rays indicated on this instrument is approximately 2 μR/h.

12.1.2 Gamma Measurement Results

Radiation fields were not significantly higher in the vicinity of these houses than in the general area. The radiation field in the house and on the site is noted in the house description in the Appendix, and Table XVII summarizes the measured gamma radiation levels at each house. The elevated exposure rates associated with the brick walls of some houses are not uncommon. Exposure rates from bricks vary greatly, depending on the source of the clay, but values in this range are not uncommon if the clay has more than the average concentration of potassium.

12.2 LOCAL GEOLOGY

This area of Ohio is at the southern edge of the last glaciation, and so the surficial geology is highly confused. The land is generally flat, and the underlying near-surface bedrock is an extensively fractured limestone, which is exposed in road cuts at major changes in elevation, and on the banks of incised rivers. The surface geology is complicated by glacial reworking. There is a surface layer of clay 1 to 3 metres thick over the whole area. Much of the clay is glacial till, and often contains small granite stones, showing that its original source was from much further north, and there are large gravel hills (moraines) to the south and west of Dayton. At the northern end of the area the bedrock is close to the surface, and the limestone is often exposed during the installation of swimming pools. At the southern end, the bedrock is usually covered with a layer of compacted gravel, with a clay surface layer.

The gravel deposits are exploited as aggregate sources, either by excavating hills or dredging pits. The pits are full with water to within a few metres of the surface, showing that the local water table is high. The water-table at the Dayton municipal well-field, which is depressed due to consistent pumping, is less than 12 m below the surface under normal conditions. Some home-owners have wells for their domestic water supply. The wells are shallow, and provide very hard water, consistent with a limestone aquifer.

12.2.1 Comment on Geology and Radon Transport

These geological conditions would seem to be unfavorable for elevated radon concentrations in houses on the flat areas, for the high water table should limit the volume of unsaturated bedrock that could be accessed by a house, and the prevalence of clay in the surface materials should lower the permeability and limit the volume of soil gas that could flow into a house.

The expectation before the houses were chosen was that the places with elevated radon concentrations would be built on gravel deposits, where the permeability was high. However, only one of the 49 houses with elevated radon concentrations that was visited was located on top of a

Table XVII. GAMMA RADIATION FIELDS

HOUSE	INDOOR FIELD (μR/h)		OUTDOOR FIELD (μR/h)		
ID #	RANGE	MEAN	RANGE	MEAN	ADDITIONAL COMMENTS
1	4-6	5	5-11	8	bricks 13-14 μR/h; patio 6 μR/h
4	5-6	6	4-7	5	house bricks 8 μR/h
7	4-5	5	7-9	8	
11	5-6	6	5-8	6	
15	3-6	5	4-7	6	
21	4-8	6	5-7	6	
22	4-6	5	9-11	10	mainly house bricks
24	5-6	6	5-10	8	house bricks 9-12 μR/h
28	4-5	5	5-6	6	
31	3-6	5	5-8	6	
32	5-6	6	8-10	9	porches 6-7 μR/h
33	4-7	5	5-10	7	
43	5	5	7-9	8	brick facing 8-10 μR/h
45	5	5	6-8	7	garage/porch slabs 4/5 μR/h brick facing 8 μR/h
47	3-6	4	5-7	6	
49	3-5	4	5-8	7	

hill (i.e. probably on a gravel moraine). All the others were on fairly flat sites, which suggested that the local soil was probably clay over limestone.

A possible explanation for elevated radon concentrations in these houses is that the surface clay layer was only 1 to 1.5 m thick, and that there was a more permeable gravel layer beneath the clay. Installation of the services and the house foundations would breach the clay layer, and allow soil gas to enter the house from the gravel. Two home owners told us that there was a gravel layer a short distance beneath the clay, and one of them said that the concrete for the basement walls had been made on site using the gravel removed from the basement excavation.

To check if the clay surface layer was thin enough to be perforated by shallow foundations, a power-driven, hand-held auger was used to drill holes to refusal or to 2.7 m depth at the 8 houses without basements in the program. At one house the auger reached clay mixed with limestone pebbles beneath a 2 m layer of clay, at the other 7 houses the auger passed through clay alone, and did not reach the expected gravel layer. A surface gamma survey at the houses has not found any indication of elevated local uranium concentrations, which might indicate the presence of uraniferous shales as the bedrock. The clay itself appears to be the radon source for these houses.

SECTION 13

QUALITY CONTROL AND QUALITY ASSURANCE

13.1 QUALITY ASSURANCE PLAN

The Quality Assurance Project Plan (QAPP) was issued for comment in July 1987, and a revised version accepted in October 1987. The QAPP covered Quality Assurance Objectives, radiation measurement instrument calibration, sampling for airborne radiation measurements, and instrument control checks. A brief review of these topics is included in this section.

13.2 TRACK ETCH DETECTORS

Calibration and quality control of Track Etch detectors is performed by the manufacturer, Terradex. As an independent check on calibration, at least ten detectors from each batch are exposed in the EML radon chamber, and a similar number of detectors are retained unopened in the field laboratory to act as unexposed controls. Both sets are returned to the processor with fictitious house identifier codes as 'blind' controls.

The following discussion focusses on the alpha-track detectors used for the pre-mitigation measurements in the 16 selected houses during Winter 1987-88. A similar procedure was followed for the first batch of detectors installed after mitigation, and exposed from May to August 1988.

13.2.1 Zero and Calibration Checks

The average radon concentration reported for the unexposed detectors during the Winter 1987-88 pre-mitigation alpha-track campaign was "less than" 1.1 pCi/L, with an analytical uncertainty of 30%. These concentrations were large enough for the reported exposures to require a zero correction. A correction of 1.1 pCi/L was subtracted from the reported concentration for each detector.

Detectors from the pre-mitigation measurement batch were exposed to three levels in the EML radon chamber in March 1988. One set of 10 was exposed to 703 pCi.d/L, a set of 5 was exposed to 657 pCi.d/L and 2 detectors were exposed to 1788 pCi.d/L. The average ratio of reported exposure after zero correction to known exposure was 0.82. The analytical uncertainty on each measurement was reported at approximately 7%. The weighted average standard deviation of all the measurements about their mean was 11%, excluding one outlier. (The outlier read 6.6 pCi/L, and the expected reading was 37 pCi/L). As the difference between the reported and actual exposures was more than twice the standard deviation of the measurements, the zero-corrected reported exposures were adjusted by multiplying by 1.23. (See Table A-5 of Appendix A for the readings of the control set of pre-mitigation detectors and Table A-7 for the control set for first set of post-mitigation detectors).

13.2.2 Field Quality Control

The EPA "Indoor Radon and Radon Decay Product Measurement Protocols" suggest that 10% of Alpha-Track measurements should be made in duplicate for field quality control. In view of the importance of these long-term measurements to the program, and the possibility of outliers in the detector readings, this percentage was not adequate. Accordingly, all alpha-track measurements were made in triplicate. This enabled outliers to be detected, and gave a better measurement of the average radon concentration.

The average radon concentration at a location was calculated as the average of the corrected detector readings. At radon exposures in the region of 150 Bq/m^3 for 2 to 3 months, the standard deviation of a the readings from group of three detectors exposed together is about 15%, or 25 Bq/m^3 (0.6 pCi/L). Accordingly, an outlier was defined as a reading that differed sufficiently from the other two that its rejection would reduce the standard deviation of a group of three detector readings to less than 2 pCi/L or to less than 30%.

The individual detector readings for the pre-mitigation alpha-track measurements in the selected houses are shown in Table A-6 of Appendix A. One outlier was detected in 153 pre-mitigation measurement program detectors exposed in the field, and in 1 of the 17 calibration detectors exposed at the EML.

The individual detector readings for the post-mitigation alpha-track measurements in the selected houses are shown in Table A-8 of Appendix A. No outliers were detected in the detectors exposed in the field, or in the calibration detectors exposed at the EML.

2.2.3 Completeness

Results were received for all of the 189 Pre-mitigation Measurement Program detectors sent to Terradex for processing, and for all of the Post-mitigation detectors.

2.2.4 Quality Assurance Objectives and Performance

The overall alpha-track performance is shown below. The Accuracy objective for Track Etch measurements would not have been achieved for the Pre-mitigation Measurement Program if the reported exposures had not been corrected. The manufacturer's calibration was 82% of that derived from the EML exposures.

	PRECISION	ACCURACY	COMPLETENESS
QAPP Goals	<2 pCi/L (30%)	10%	100%
Actual Performance Pre-mitigation Survey	<2 pCi/L (30%)	-	100%

2.3 AB-5 RADON MONITORS

2.3.1 Calibration

The AB-5 monitors used in this program were calibrated yearly at the DOE Environmental Measurements Laboratory in New York. Before each calibration a specially modified cell containing a small emanating radium source (Check Cell) with a nominal count rate of 2000 cpm, was used to set the optimum high voltage and discriminator setting for radon measurements. To minimize the background count rate, the high voltage was set just above the plateau 'knee', approximately 60 volts onto the plateau. There was little change in the plateau shape, or the optimum high voltage setting with time.

Simultaneous measurements over 16 to 24 hours were made with the AB-5 and the laboratory standard continuous radon monitor from the large radon chamber. The radon concentration in the chamber was not changed deliberately, and varied only slightly over this period. The cell counting efficiency was determined by setting the average radon concentration as measured by the AB-5 equal to the average radon concentration in the chamber as measured by the standard monitor.

Typical count rates at equilibrium were 1.90 counts per hour per Bq/m^3 (70 counts/h per pCi/L), with backgrounds of 60 counts per hour. The precision of a single measurement at a radon concentration of 150 Bq/m^3 (4 pCi/L) is 20 Bq/m^3 (12%). An average of 6 or more readings will have a precision of at least 5%.

The relative contribution to the counts recorded in each period from the radon in the sample, and from the activity deposited in the cell by the radon in previous samples, was derived directly by switching the monitor input from the radon chamber to low radon air, and following the change in count rate with time.

A two term polynomial correction was sufficient to correct for activity deposited in the cell by previous samples. The equation used was:-

$$R_n = (C_n - 0.3C_{n-1})/(0.7K)$$

where R_n is the radon concentration of the n'th sample, C_n is the net count over the 50 minutes following the sample, C_{n-1} is the net count for the 50 minutes following the preceding n-1'th sample, and K is the number of counts in 50 minutes for a radon concentration of 1 pCi/L.

The calibration factors (0.7K) to give radon concentrations in pCi/L as determined at each calibration for each monitor are shown in Table XVIII. The calibration factor and background count-rate for each monitor/cell combination is included in the BASIC program used to convert raw data to radon concentrations and is called automatically by the program.

Monitor 206 was not calibrated in July 1987 as it had been returned to the manufacturer for repair of the charging circuit, and monitor 213 was not with the project at that time.

13.3.2 Field Quality Control

Field quality control was maintained by two 285 cm^3 scintillation cells. One was an ordinary cell which was kept closed and therefore contained very little radon (Blank Cell). The other was a specially modified cell containing a small emanating radium source (Check Cell). These cells were counted in the units on a monthly basis to check that the machines were operating properly.

13.3.3 Completeness

The AB-5 has an internal gel-cell battery which will operate the machine in the quasi-continuous mode for 24 to 48 hours, depending on the initial state of charge, and will maintain the memory for 1 to 4 days. The machines normally run on AC power, and are unaffected by temporary power interruptions. However, 4 runs did not last for more than 24 hours when the machines were operated on battery power in unheated crawlspaces in cold weather. All the data was lost from one completed run when the on/off switch was accidentally pushed twice. The first time stops the machine, the second time starts the machine on a new run, and erases the data stored in the memory.

Table XVIII. AB-5 CALIBRATION FACTORS

MONITOR	CALIBRATION DATE		
UNIT #	JUNE 1985	JULY 1986	JULY 1987
203	40.5	43.5	43.2
206	42.9	40.5	---
213	44.3	42.6	---
228	43.0*	41.8	42.0
238	46.0*	42.0	42.5
255	---	43.1	40.4
256	---	42.3	40.8
257	---	45.7	43.0

*cell calibrated alone, not complete machine.

The sum of the systematic and counting uncertainties in the calibration factor amounted to about 1%, or 0.5.

The AB-5 memory contents are transferred to a portable computer via a parallel-to-serial converter and a RS-232 interface. The computer calculates the radon concentrations, produces a hard copy report, and drives a plotter to provide a convenient summary of the data. The data is stored in a condensed form on 3.5 inch disks. Results are later transferred to standard 5 inch floppy disks for information exchange. There were no data losses attributable to the storage system.

13.3.4 Quality Assurance Objectives and Performance

The Quality Assurance Objectives for the AB-5 monitors were met. The average radon concentration was always calculated over at least a day, which represents 24 measurements. Six measurements would give a precision of 5%. The change in calibration factor from one calibration to the next was less than 5%.

	PRECISION	ACCURACY	COMPLETENESS
QAPP Goals	<5%	5%	95%
Actual Performance	<5%	5%	97%

13.3.5 Problems

The Check Cell had been modified from a standard cell, and still had the self-sealing connectors. There was a slight leak in the cell, probably at the connectors, and the count rate of the cell was affected by changes in atmospheric pressure. Count rates varied from 2 200 to 2 600 cpm. To allow precise comparisons of the machines, a scintillation cell simulator was constructed with an ^{241}Am source and a scintillation disk mounted at the end of a tube. The pulse height spectrum from this was similar to that from a cell, and the count rate was unaffected by atmospheric pressure changes. The count rate of this simulator, which tests the electronic portions of the machines, varies from machine to machine by less than 2%, and indicates that the machines essentially identical in electrical performance when set correctly.

13.4 SCINTILLATION CELL MEASUREMENTS

Scintillation cells are used to make grab sample measurements of the radon concentration in ducts and in soil gas. The cells used are plastic bodied cells with nominal volumes of 0.1, 0.5, and 1.5 litre, with nominal sensitivities of 0.5, 2.2, 4.5 cpm per pCi/L. They are counted on a 120 mm diameter photomultiplier tube, with a background count rate of less than 1 cpm at the operating voltage. The cells have a background of less than 2 cpm.

Selected cells were calibrated by sampling from the EML radon chamber, and those cells were subsequently compared with the other cells by sampling from a sample of soil gas collected in a 100 litre plastic bag. The sensitivities of all the cells did not vary by more than 10% from the nominal value.

13.4.1 Scintillation Cell Field Quality Control

Scintillation cells were inspected at each use for damage, such as broken or loose valves, cracks, or loss of scintillation covering. The photomultiplier and scaler combination used to count the cells was checked monthly with the Check Cell. Four cells were removed from service, one with a broken valve, and three for loss of scintillation coating. Eight new 0.1 L cells were added.

13.4.2 Completeness

The equipment was reliable. Results were obtained for all of the radon samples taken in the houses.

13.4.3 Quality Assurance Objectives And Performance

The Quality Assurance Objectives for the scintillation cells were met. The concentrations measured were all high enough that the precision of individual measurements was greater than 50%, the calibration factors were not more than 10% in error, and all samples taken were measured.

	PRECISION	ACCURACY	COMPLETENESS
QAPP Goals	<50%	20%	75%
Actual Performance	<50%	10%	100%

13.5 AUDITS

13.5.1 EPA Audits

No EPA Field Audits were conducted during the first field phase of this program, February — April 1988.

13.5.2 Internal Audits

An internal audit was carried out in April 1988 by an Acres Quality Control Specialist to ensure that Quality Control and Assurance procedures as laid down in the QAPP were being followed.

All data collected had been properly transferred to the house files from the field notebooks and other data sources.

13.6 RADON MEASUREMENT PROFICIENCY PROGRAM

In 1986 the EPA introduced a Radon/Radon Progeny Measurement Proficiency Evaluation Program to evaluate the performance of the many firms that were entering the field of radon measurements. Measuring devices were exposed 'blind' in intercomparison rounds, and the concentrations measured were compared by the organizers with the known concentrations, and the performance evaluated by them.

No intercomparison round was carried out during Phase 1 of this project.

APPENDIX A

SUMMARY TABLES

Table 1. PRE-SELECTION RADON CONCENTRATION SUMMARY

HOUSE	CHARCOAL TEST**			PYLON AB-5 RESULTS		
NO.	DATE	pCi/L	LOCATION	DATE	pCi/L	LOCATION
01	02/87	16.4	living area	01/88	19.6	bedroom
04	02/87	45.9	basement (near sump)	01/88	44.3*	basement
07	12/87	12	basement	01/88	11.9	basement
	02/87	25.8	over floor drain			
11	02/87	28.8	basement	01/88	16.6	slab on grade
	12/87	33.3	basement			
15	02/87	26.6	under tub	01/88	16.2*	living room
21	02/87	93.0	basement	01/88	11.4	living room
22	02/87	22.5	crawl space	01/88	33.5	crawl space
				01/88	24.8	living room
24	02/87	51.4	crawl space	01/88	27.6	crawl space
				01/88	13.6	living room
28	02/87	19.0	crawl space	01/88	20.5	crawl space
				01/88	14.5	living room
31	02/87	18.0	bedroom	01/88	16.4	living room
32	02/87	37.9	basement	01/88	24.4	basement
33	02/87	18.2	living room	01/88	11.5	living room
				01/88	26.3	crawl space
43	02/87	22.8	basement	01/88	16.5	basement
	12/87	8.5	living room			
45	12/87	26	basement	01/88	19.8	basement
	02/87	117	over floor drain			
47	02/87	20.5	living area	01/88	25.4	living room
49	02/87	9.0	basement	01/88	8.7*	basement

* RAPCA femto-TECH R210F used

** from RAPCA data base

Table 2. HOUSES SELECTED FOR PHASE 1 WORK

HOUSE NO.	TYPE	FOUNDATION CONSTRUCTION	LOCATION	AVERAGE OF PRE-SELECTION READINGS (pCi/L)
01	slab-on-grade	block	Beavercreek	18
04	basement	block	Springfield	46
07	basement	poured	Springfield	12
11	basement (plus slab-on-grade)	poured	Spring Valley	24
15	slab-on-grade	poured	Xenia	16
21	slab-on-grade (basement)	poured filled block	Xenia	11 (93)
22	crawl space	block	Troy	25
24	crawl space	block	Troy	14
28	crawl space	poured	Tipp City	15
31	slab-on-grade	poured	Fairborn	17
32	basement	poured	Fairborn	31
33	crawl space	block	Fairborn	15
43	basement	poured	Kettering	20
45	basement	poured	Dayton	23
47	slab-on-grade	poured	Dayton	23
49	basement	poured	Bellbrook	9

Table 3. PRE-MITIGATION RADON CONCENTRATION SUMMARY

HOUSE	ALPHA-TRACK RESULTS			PYLON AB-5 AVERAGES		
NO.	PERIOD	pCi/L	LOCATION	DATE	pCi/L	LOCATION
01	12/87-3/88	20.9	bedroom	1-2/88	20.2	bedroom
	12/87-3/88	17.5	kitchen			
04	12/87-3/88	24.5	basement	1-3/88	35.8	basement
	12/87-3/88	20.7	living area			
07	12/87-3/88	10.1	basement	1-2/88	10.9	basement
	12/87-3/88	9.5	hallway			
11	12/87-3/88	28.9	basement	1-3/88	23.2	basement
	12/87-3/88	17.3	living area	1-3/88	16.6	living area
15	12/87-3/88	16.2	bedroom	1-2/88	17.9	living area
21	12/87-3/88	98.6	basement	2/88	125.1	basement
	12/87-3/88	12.7	living area	1-2/88	12.6	living area
22	12/87-3/88	25.6	crawl space	1-4/88	27.3	crawl space
	12/87-3/88	15.0	kitchen	1-4/88	17.0	living area
24	12/87-3/88	21.1	crawl space	1-4/88	32.5	crawl space
	12/87-3/88	11.2	hallway	1-4/88	15.9	living area
28	12/87-3/88	20.7	crawl space	1-3/88	29.4	crawl space
	12/87-3/88	13.4	kitchen	1-3/88	7.7	living area
31	12/87-3/88	14.0	bedroom	1-2/88	14.7	living area
	12/87-3/88	12.6	kitchen			
32	12/87-3/88	23.2	basement	1-2/88	27.0	basement
	12/87-3/88	17.6	bedroom			
	12/87-3/88	17.4	dining room			
33	12/87-3/88	8.4	kitchen	1-4/88	16.6	living area
	12/87-3/88	17.6	crawl space	1-4/88	41.3	crawl space
43	12/87-3/88	11.3	laundry	1-3/88	14.3	basement
	12/87-3/88	8.0	workroom			
	12/87-3/88	6.3	living area			
45	12/87-3/88	19.2	basement	1-3/88	20.5	basement
	12/87-3/88	8.4	living area			
47	12/87-3/88	24.1	bedroom	1-2/88	29.6	living area
	12/87-3/88	22.9	kitchen			
49	12/87-3/88	4.8	basement	1/88	5.8	basement
	12/87-3/88	4.0	living area			

Table 4. COSTS OF PHASE 1 MITIGATIVE WORK

TREATMENT	HOUSE NO.	SYSTEM COSTS ($)		
		TEMPORARY	TEMPORARY	PERMANENT
Sub-slab Ventilation				
	01	627	610	809
	07	556	-	882
	11	994	312	1018
	15	891	488	647
	21	1258	-	684
	31	1437	-	-
	43	751	-	1615
	45	1132	-	1611
	47	1234	-	625
Crawl-space Ventilation				
	22	586	-	241
	24	439	-	768
	28	782	-	308
	33	621	-	352
Sump Ventilation				
	04	1136	-	1822
	32	1540	-	747
Caulking				
	32	-	-	1789
	49	-	-	1823

Table 5. ZERO CHECKS AND CALIBRATION CHECKS ON ALPHA-TRACK DETECTORS USED IN PRE-MITIGATION MEASUREMENTS (WINTER 1987-88)

ZERO CHECK Results reported for detectors which had not been exposed to radon (blanks).

Detector No.	Reported Concentration (pCi/L)	Mean (pCi/L)
5491	1.1	1.07
5492	1.1	
5512	1.1	
5515	0.7	
5524	1.1	
5525	1.1	
5462	1.1	
5463	1.1	
5473	1.1	
5474	1.1	
5477	1.1	
5499	1.1	
5519	1.1	

CALIBRATION CHECK Results reported for detectors exposed to known concentration.

Detector No.	Expected Concentration (pCi/L)	Reported Concentration (pCi/L)	Correction (Expected/ Reported)*
5216	34.6	24.8	1.35
5471	34.6	25.6	1.31
5472	34.6	24.8	1.35
5479	34.6	27.9	1.20
5504	34.6	27.4	1.22
5249	37.0	26.6	1.35
5469	37.0	33.6	1.07
5452	37.0	35.7	1.01
5453	37.0	6.6	—
5447	37.0	35.9	1.00
5500	37.0	28.2	1.27
5509	37.0	27.0	1.33
5510	37.0	24.3	1.48
5511	37.0	29.3	1.23
5517	37.0	34.3	1.05
5522	45.0	37.6	1.17
5523	45.0	36.3	1.21

Average calibration correction factor: 1.23

* Calculated accounting for the zero correction (1.07 pCi/L).

Table 6. TRIPLICATE ALPHA-TRACK DETECTOR RESULTS FROM PRE-MITIGATION MEASUREMENTS IN THE HOUSES SELECTED FOR PHASE 1

House No.	Location	Detector No.	Reported Concentration (pCi/L)	Mean (pCi/L)	Standard Deviation	Corrected Concentration (pCi/L)*
1	Kitchen	5377	16.8	15.37	1.24	17.5
	Kitchen	5379	14.6			
	Kitchen	5327	14.7			
1	Bedroom	5359	18.0	18.10	0.95	20.9
	Bedroom	5409	19.1			
	Bedroom	5253	17.2			
4	Basement	5406	23.3	21.07	1.93	24.5
	Basement	5403	20.0			
	Basement	5370	19.9			
4	Upstairs	5399	18.0	17.97	1.45	20.7
	Upstairs	5304	19.4			
	Upstairs	5365	16.5			
7	Basement	5363	9.5	9.30	0.35	10.1
	Basement	5404	9.5			
	Basement	5364	8.9			
7	Upstairs	5397	8.9	8.80	0.36	9.5
	Upstairs	5405	8.4			
	Upstairs	5400	9.1			
11	Basement	5372	22.3	24.67	2.63	28.9
	Basement	5374	24.2			
	Basement	5394	27.5			
11	SOG	5312	16.8	15.20	1.65	17.3
	SOG	5373	15.3			
	SOG	5395	13.5			
15	Bedroom	5369	14.8	14.33	0.42	16.2
	Bedroom	5366	14.0			
	Bedroom	5402	14.2			
21	Basement	5323	88.9	81.57	12.70	98.6
	Basement	5413	88.9			
	Basement	5317	66.9			
21	Upstairs	5310	11.5	11.40	0.66	12.7
	Upstairs	5322	12.0			
	Upstairs	5316	10.7			

(continued)

Table 6. (CONTINUED)

House No.	Location	Detector No.	Reported Concentration (pCi/L)	Mean (pCi/L)	Standard Deviation	Corrected Concentration (pCi/L)*
22	Kitchen	5391	12.0			
	Kitchen	5263	13.8	13.33	1.17	15.0
	Kitchen	5392	14.2			
22	Crawl space	5344	20.5			
	Crawl space	5390	23.3	22.00	1.41	25.6
	Crawl space	5375	22.2			
24	Hall	5261	8.9			
	Hall	5346	9.4	10.20	1.84	11.2
	Hall	5345	12.3			
24	Crawl space	5255	5.8			
	Crawl space	5254	28.0	18.27	11.35	21.1
	Crawl space	5357	21.0			
28	Kitchen	5353	8.3			
	Kitchen	5250	14.2	12.00	3.22	13.4
	Kitchen	5231	13.5			
28	Crawl space	5262	17.3			
	Crawl space	5351	20.3	17.97	2.08	20.7
	Crawl space	5350	16.3			
31	Kitchen	5240	11.6			
	Kitchen	5341	11.8	11.37	0.59	12.6
	Kitchen	5340	10.7			
31	Bedroom	5244	11.4			
	Bedroom	5243	14.2	12.47	1.51	14.0
	Bedroom	5215	11.8			
32	Basement	5226	19.4			
	Basement	5225	19.9	19.97	0.60	23.2
	Basement	5493	20.6			
32	Upstairs (DR)	5213	17.3			
	Upstairs (DR)	5495	13.6	15.30	1.87	17.4
	Upstairs (DR)	5223	15.0			
32	Upstairs (BR)	5503	17.5			
	Upstairs (BR)	5501	14.5	15.47	1.76	17.6
	Upstairs (BR)	5507	14.4			

(continued)

Table 6. (CONTINUED)

House No.	Location	Detector No.	Reported Concentration (pCi/L)	Mean (pCi/L)	Standard Deviation	Corrected Concentration (pCi/L)*
33	Kitchen	5256	8.4	7.90	0.46	8.4
	Kitchen	5331	7.8			
	Kitchen	5207	7.5			
33	Crawl space	5234	14.5	15.43	0.95	17.6
	Crawl space	5229	16.4			
	Crawl space	5220	15.4			
43	Bsmt workrm	5212	8.7	7.60	0.96	8.0
	Bsmt workrm	5342	6.9			
	Bsmt workrm	5247	7.2			
43	Bsmt laundry	5235	9.4	10.30	0.79	11.3
	Bsmt laundry	5356	10.9			
	Bsmt laundry	5354	10.6			
43	Upstairs	5241	6.0	6.23	0.49	6.3
	Upstairs	5239	6.8			
	Upstairs	5355	5.9			
45	Basement	5339	16.7	16.70	0.10	19.2
	Basement	5245	16.8			
	Basement	5237	16.6			
45	Upstairs	5233	8.4	7.97	0.67	8.4
	Upstairs	5232	7.2			
	Upstairs	5246	8.3			
47	Kitchen	5334	19.8	19.73	0.12	22.9
	Kitchen	5206	19.6			
	Kitchen	5330	19.8			
47	Bedroom	5332	21.1	20.73	0.35	24.1
	Bedroom	5352	20.4			
	Bedroom	5224	20.7			
49	Basement	5410	5.3	5.00	0.79	4.8
	Basement	5260	4.1			
	Basement	5361	5.6			
49	Upstairs	5360	4.1	4.30	0.20	4.0
	Upstairs	5329	4.3			
	Upstairs	5326	4.5			

*The corrected concentration includes the zero and the calibration corrections.

Table 7. CALIBRATION CHECKS FOR MAY TO AUGUST 1988 ALPHA-TRACKS

ZERO CHECKS - UNEXPOSED DETECTORS

Detector #	Reported Conc.
827901	0.7
828068	0.8
827971	0.7
827979	0.4
828029	0.5
828099	0.8
828056	0.4
828064	0.8
828149	0.4
827927	0.7
828019	1.0
828059	1.0

MEAN READING OF UNEXPOSED DETECTORS = 0.68 pCi/L
Standard Deviation = 0.22 pCi/L

CALIBRATION CHECK - DETECTORS EXPOSED TO 2.81 pCi/L

Detector #	Reported Conc.
828084	2.7
828093	3.2
828066	3.1
827982	2.6
828089	2.9
828054	1.8
828057	2.2
828092	3.1
828077	2.5
827974	2.6
828083	3.1
828078	3.4

MEAN REPORTED EXPOSURE = 2.77 pCi/L
Standard Deviation = 0.46 pCi/L

CALIBRATION CORRECTION FACTOR (INCLUDING ZERO CORRECTION) = 1.30

Table 8. TRIPLICATE ALPHA-TRACK MEASUREMENTS MAY TO AUGUST 1988

House #	Location	Detector #	Reported Conc. pCi/L	Mean pCi/L	Dev. pCi/L	Corrected Conc. pCi/L
01*	Living Area	828140	7.0			
	Living Area	828131	8.9			
	Living Area	828142	7.6	7.83	0.97	9.64
04	Basement	828146	1.1			
	Basement	828074	1.8			
	Basement	828136	1.9	1.60	0.44	1.24
04	Living Area	828076	1.5			
	Living Area	828121	2.0			
	Living Area	828153	1.6	1.70	0.26	1.37
07	Basement	828106	1.5			
	Basement	828009	2.5			
	Basement	828105	2.4	2.13	0.55	1.96
07	Living Area	828007	1.4			
	Living Area	828141	1.4			
	Living Area	828147	1.6	1.47	0.12	1.06
11	Basement	827985	2.6			
	Basement	828117	2.1			
	Basement	828114	2.5	2.40	0.26	2.32
11	Family Rm.	828152	1.5			
	Family Rm.	828118	1.6			
	Family Rm.	828013	1.3	1.47	0.15	1.06
11	Living Area	828111	1.3			
	Living Area	827972	1.2			
	Living Area	827956	1.2	1.23	0.06	0.74

* INDICATES MITIGATION WORK NOT COMPLETE AT TIME OF MEASUREMENT

(continued)

Table 8. (CONTINUED)

House #	Location	Detector #	Reported Conc. pCi/L	Mean pCi/L	Dev. pCi/L	Corrected Conc. pCi/L
15	Living Area	828038	2.9			
	Living Area	828030	2.0			
	Living Area	828015	2.4	2.43	0.45	2.36
21	Basement	828001	3.7			
	Basement	827994	5.0			
	Basement	827993	3.2	3.97	0.93	4.43
21	Living Area	827921	1.6			
	Living Area	828060	1.9			
	Living Area	828003	1.7	1.73	0.15	1.42
22*	Crawlspace	828012	6.1			
	Crawlspace	828016	7.4			
	Crawlspace	828034	6.4	6.63	0.68	8.03
22*	Living Area	828113	3.5			
	Living Area	827995	3.2			
	Living Area	828041	4.1	3.60	0.46	3.93
24*	Crawlspace	827915	10.5			
	Crawlspace	828137	10.4			
	Crawlspace	828112	10.9	10.60	0.26	13.38
24*	Living Area	828081	4.2			
	Living Area	828107	6.8			
	Living Area	828133	7.1	6.03	1.59	7.22
28*	Crawlspace	828155	3.9			
	Crawlspace	828129	3.7			
	Crawlspace	827905	3.2	3.60	0.36	3.93
28*	Living Area	827916	1.4			
	Living Area	827904	1.7			
	Living Area	828124	2.7	1.93	0.68	1.69

* INDICATES MITIGATION WORK NOT COMPLETE AT TIME OF MEASUREMENT

(continued)

Table 8. (CONTINUED)

House #	Location	Detector #	Reported Conc. pCi/L	Mean pCi/L	Dev. pCi/L	Corrected Conc. pCi/L
31*	Living Area	828127	7.8			
	Living Area	828075	7.0			
	Living Area	828138	8.3	7.70	0.66	9.46
32	Basement	828128	4.3			
	Basement	828008	4.2			
	Basement	828134	4.0	4.17	0.15	4.70
32	Living Area	828108	2.2			
	Living Area	828130	2.2			
	Living Area	828006	2.4	2.27	0.12	2.14
33*	Crawlspace	827984	5.5			
	Crawlspace	828148	5.9			
	Crawlspace	828150	6.9	6.10	0.72	7.31
33*	Living Area	827918	2.6			
	Living Area	828104	2.5			
	Living Area	828010	3.3	2.80	0.44	2.85
43	Basement	828116	2.3			
	Basement	828151	2.5			
	Basement	828047	2.3	2.37	0.12	2.27
43	Living Area	828045	1.9			
	Living Area	828000	1.3			
	Living Area	827990	1.2	1.47	0.38	1.06
45	Living Area	828143	1.9			
	Living Area	827970	1.5			
	Living Area	827964	1.1	1.50	0.40	1.10
45	Basement	827963	1.6			
	Basement	828025	1.7			
	Basement	828145	1.0	1.43	0.38	1.01

* INDICATES MITIGATION WORK NOT COMPLETE AT TIME OF MEASURMENT

(continued)

Table 8. (CONTINUED)

House #	Location	Detector #	Reported Conc. pCi/L	Mean pCi/L	Dev. pCi/L	Corrected Conc. pCi/L
47	Living Area	828036	3.2			
	Living Area	827926	1.5			
	Living Area	828026	2.0	2.23	0.87	2.09
49	Basement	828002	3.7			
	Basement	828014	3.2			
	Basement	827931	3.2	3.37	0.29	3.62
49	Living Area	827913	2.0			
	Living Area	827914	1.3			
	Living Area	828115	1.6	1.63	0.35	1.28

APPENDIX B

PUBLICATIONS

Presentations arising from the work carried out under this project:

1. Henschel, D. B., A. G. Scott, W. O. Findlay and A. Robertson, "Testing of Indoor Radon Reduction Methods in 16 Houses Around Dayton, Ohio", in *Proceedings: The 1988 Symposium on Radon and Radon Reduction Technology*. Volume 1. Symposium Oral Papers, EPA-600/9-89-006a, March 1989. (NTIS No PB 89-167480).

2. Scott, A. G., "Effect of Indoor Radon Variability on the Duration and Interpretation of Radon Measurements", in *Proceedings: The 1988 Symposium on Radon and Radon Reduction Technology*. Volume 1. Symposium Oral Papers, EPA-600/9-89-006a, March 1989. (NTIS No PB 89-167480).

APPENDIX C

HOUSE DESCRIPTIONS

NOTES ON APPENDIX C

A detailed description of the work carried out in each house is provided in this section.

The following notes will aid in interpretation of the tables, figures and graphs for each house.

TABLES

Each house description includes at least two tables: one summarizing the individual Pylon measurements made in the house; and one summarizing measurements made on the mitigation system(s) installed.

The key to the shorthand notes used in the tables.

h.p.	heat pump.
DPmax	mitigation fan operated to produce maximum suction in system (fan at full speed).
0.5 DPmax	mitigation fan controller turned down to reduce suction in system to about half that at maximum speed.
at hole A	pressure differential across the slab, or radon concentration measured under the slab, at test hole A. (Sub-slab is usually at lower pressure if SSV system operating in suction, at higher pressure if system in pressure or if no system operating).
in riser	suction (or pressure), flow rate or radon concentration measured inside SSV pipe near penetration through slab or sump cover.
at fan	suction (or pressure), flow rate or radon concentration, measured in SSV pipe near mitigation fan.

FIGURES

Each house description includes a number of figures, including graphs of the hourly radon measurements, floor plans of the house, and sometimes diagrams of the mitigation system.

The information given on the radon concentration versus time graphs is:

> The starting time of the Pylon monitoring period is given in the form:-
> START TIME 88 2 27 9.45 (i.e., monitoring period began at 9:45 a.m. on February 27, 1988).
>
> System operating conditions during the course of a measurement period, and other notes, are given at the top of the graph:-
> e.g., FAN SPEED ADJUSTED TO GIVE 0.5 DPmax 3/11/14:40 (i.e., fan adjusted to operate at half maximum suction at 2:40 p.m. on March 11).

HOUSE 01

1 GENERAL DESCRIPTION

This large slab-on-grade house (160 m^2) with attached double garage was built in 1986 as an in-fill in a 25-year-old suburban subdivision in Beavercreek. The perimeter foundation wall of the house is concrete block including the garage exterior walls. The garage floor was apparently poured integral with the house floor slab, and there are no footings for the non-loadbearing frame walls between the house and the garage. The exterior walls are of brick. The floor in the hall, kitchen, utility room, and two bathrooms is covered with sheet vinyl, the remainder is covered with fitted carpet, applied over bare concrete. Water is supplied by a well, but there is sewer service. Heating is by a down-draft forced-air electric heat pump located in a central closet, with metal heat distribution ducts running radially beneath the floor slab to metal register boxes.

2 INVESTIGATION

In January 1988 a short-term radon measurement made as part of the pre-selection process found that over 45 hours the concentration ranged from 13 to 32 pCi/L and averaged 19.6 pCi/L.

In early February 1988 the furnace fan was switched from normal cycling ("automatic") to run continuously, in order to investigate the role of the sub-slab heating system ducts on the entry of soil gas and radon. The fan would pressurize the ducts and prevent entry of soil gas, and would also pressurize the sub-slab fill as a result of leakage from the duct system, and thus should reduce the flow rate of soil gas containing radon from the soil towards the house.

Continuous fan operation had no apparent effect. With the fan cycling on "Auto", the radon concentration over 4 days ranged from 14 to 29 pCi/L, averaging about 21.5 pCi/L (see Figure 01-2). With the fan on continuous run, the range over 2 days was 15 to 27 pCi/L, averaging 21.2 pCi/L; and with the fan returned to "Auto", the range over 2 days was 14 to 23 pCi/L, averaging 17.6 pCi/L (see Figure 01-3).

This house does not have an inspection panel for the plumbing. The owner, who had watched the house being built, said that the bath was first placed on the slab, and then the bathroom frame walls were built round it. If this was the case, there would have been no need to provide access through the wall so that the drain could be connected when the bath was installed. In late February 1988, a borescope was inserted into the space beneath the bath through an electrical outlet in an adjoining wall, but no opening around the bath drain pipe could be seen. The slab is probably poured around the plumbing without an opening.

A sub-slab fill connectivity test was carried out in late February 1988. A 30 mm hole (A) was drilled in the garage floor slab approximately 1 m from the house corner, exposing pea gravel beneath the slab, and a 12-mm diameter test hole (B) was drilled in the living room floor about 30 cm from the garage wall, exposing pea gravel. A suction of 3100 Pa was produced in the garage hole, and a suction of 25 Pa was measured in the test hole. A second test hole (C) was drilled in a bedroom about 8 m away from hole B, and also exposed pea gravel, but no visible effect was produced on the flow of soil gas from the sub-slab space (as visualized with smoke) by evacuating the garage hole or by applying 6500 Pa suction directly to test hole B.

The poor communication despite high sub-slab permeability (several cm thickness of pea gravel) suggested that the sub-slab heating ducts were acting as an obstacle. A heating duct passes diagonally under the bedroom floor, and so a third test hole (D) was drilled 4 m away through the bedroom floor on the opposite side of the duct, and 2500 Pa suction applied. There was a slight decrease in sub-slab pressure at C (<1 Pa), and airflow was reversed through the hole. A fourth hole (E) was drilled 2.5 m away from C on the same side of the duct, and when 1800 Pa suction was applied, the sub-slab pressure at C decreased by 6 Pa, but there was no detectable change in the pressure or the rate of air movement out of the hole at D. This was taken as confirmation that the sub-slab heating ducts did effectively divide the sub-slab space up into a number of compartments with poor communication between them.

Operation of the furnace fan raised the pressure underneath the slab. At hole B, the pressure increase was 10 Pa; at hole C, 4 Pa, and at hole D, less than 1 Pa. The furnace plenum pressure was 45 Pa. It is of interest that radon reductions in the house were so limited, given the apparently good sub-slab pressurization. One possible explanation is that, despite the good pressurization, there may not have been sufficient air flow underneath the slab to sweep the radon away; what radon did enter the sub-slab space was forced into the house through entry routes as a result of the pressurization.

Sub-slab radon concentrations were low. Air samples were taken from beneath the floor immediately after drilling at hole A were 45 pCi/L; and at hole C 15 pCi/L. Radon concentrations in the exterior walls were measured through electrical outlet openings in the front and rear walls, and were respectively 8 and 5 pCi/L; the house air concentration was also 5 pCi/L at the time of the sub-slab and in-wall measurements. The fact that the ratio of indoor concentrations to sub-slab concentrations is so high suggests that the sub-slab gas finds it very easy to enter the house.

Freon was injected beneath the floor slab, through hole C with the furnace fan off. No freon was detected entering the house through the heating duct or either of the nearby test holes in 20 minutes, nor even when the furnace fan was turned to continuous run for a further 15 minutes.

The sub-slab material had good permeability, but the radial heating ducts divided the sub-slab space into virtually independent compartments, and so the effect of a single point sub-slab ventilation system would be confined largely to the compartment it was placed in.

3 EXPERIMENTAL INSTALLATIONS

The mitigation system selected for demonstration at this house was sub-slab ventilation. The system was planned in two stages: a temporary system to check the effectiveness of the system, followed by a permanent installation. It was decided to test a single exhaust point where it would access the largest compartment of the sub-slab fill. The first location chosen was in the garage, close to where the test hole had been drilled. This would ventilate the fill beneath both the living room and the family room, and could be installed, and removed if necessary, with no disruption of the finished areas.

An exhaust system was installed in early March 1988. A 12-cm diameter hole was drilled in the concrete garage slab about 15 cm from the living-room wall. The material beneath the slab was found to be a pit-run gravel with considerable fine material, but the larger stones had worked to the top, giving the appearance of a pea gravel. A temporary ventilation system was installed, using rigid "4-inch" diameter PVC pipe that was run across the garage beneath the ceiling to a fan mounted in a sheet of plywood placed in the garage side door opening. The side door was removed to make this possible. With the fan operating at full speed, the radon concentration in the pipe was 85 pCi/L, and the flow in the pipe was 7 L/s at a pressure of 320 Pa, and at low speed, the flow was 3 L/s at 150 Pa.

The radon concentration in the house air with the fan at full speed ranged from 4 to 22 pCi/L, averaging 9.9 pCi/L over a 41 hour period with the fan on high speed, and from 4 to 31 pCi/L, averaging 19.9 pCi/L over a 37 hour period with the fan on low speed. A second test run was made with the fan on high speed continually, and the radon concentration after the fan had been in operation for 6 days ranged from 2 to 23 pCi/L, averaging 9.6 pCi/L over 98 hours. This wide variation in concentration showed that although the system decreased the average entry rate of soil gas and radon into the house, there were still large untreated routes of entry. A more effective location for the system was needed.

It had been intended to improve system efficiency by deepening the exhaust hole to reach the layer of permeable gravel or limestone that was believed to lie beneath the surface layer of clay. A hand-held power auger had been obtained to do this without extensive digging. To check the depth of hole that might be needed, a test hole was drilled at the rear of the house. The top 20 cm was an organic loam, underlain by a heavy clay. The auger was unable to penetrate more than 80 cm through this clay before stalling. It was clear that deepening the hole would be a major task, and probably could not be carried out with the equipment available.

It was decided to remove the existing system and try a second location that might ventilate the sub-slab fill more effectively. Discussions were held with the homeowner as to where an acceptable location would be for a second temporary exhaust location. An interior locatiaon was not desired by the owner, and would require a considerable expense to restore the finish, so an alternative exterior location was chosen. The foundation wall at this house was made of at least 3 courses of hollow concrete block, with the uppermost course closed at the top, and so it was possible to use the wall as an exhaust collector, and thereby ventilate a wide expanse of the sub-slab fill from one point.

In early April 1988, the exhaust system in the garage was removed, the hole in the garage floor filled with concrete, and the garage side-door replaced. An exhaust hole was drilled into the outer face of the block foundation wall near the center of the rear wall, and after verifying that the top course of blocks was closed, the hole was enlarged to about 10 cm diameter and a toilet-flange adaptor screwed over the hole. A temporary T-2 exhaust fan in a box was attached to the flange by flex-duct. When the fan was turned on at high speed, the radon concentrations in the house air fell rapidly, and over the next 49 hours ranged from 1 to 8 pCi/L, averaging 4.3 pCi/L. The furnace circulation-fan was then turned to continuous run, to simulate maximum heating in winter or cooling in summer. Radon concentrations increased, ranging from 6 to 15 pCi/L, and averaging 9.4 pCi/L over 38 hours.

The system was tested and modified in late April to draw more air from beneath the floor slab. Prior to modification, and with the fan on high speed, the flow was about 30 L/s, at a radon concentration of 20 pCi/L. A 5 second pulse of freon gas was injected at a weephole in the exterior brick wall about 1.3 m away from the fan exhaust hole, and was detected at the fan within seconds, but then continued to arrive at the fan for many minutes following. A similar freon pulse at a weephole 4 m away apparently did not arrive at the fan, for no increase in freon concentration was detected over 10 minutes following the injection.

The flange was unscrewed from the wall, and two 30-mm diameter holes were drilled through the opposite inner face of the block wall to enter the sub-slab fill. These holes revealed that there was 25 mm of beadboard perimeter insulation between the sub-slab fill and the interior surface of the block wall. This meant that the effective leakage area from the wall to the fill was much less than if there had been only sub-slab insulation, and the amount of air drawn from the sub-slab fill via small openings in the inner surface of the wall was less than anticipated.

The flange was replaced over the outer hole, and the fan reconnected. The flow from wall and sub-slab space had increased to 40 L/s, but radon concentrations in the exhaust air were now lower at 12 pCi/L, suggesting that the radon concentration in the sub-slab space was low. A freon pulse injection into a third brick wall weephole 2.5 m away from the fan exhaust hole appeared at the fan within 10 seconds of the injection, and again cleared slowly from the exhaust, but a pulse injection at 5 m from the fan did not appear in 5 minutes.

The performance of the modified system was only slightly better than before. Radon concentrations with the furnace fan on 'Auto' ranged from 0 to 3 pCi/L, averaging 1.3 pCi/L over 24 hours, but with the fan on continuous radon concentrations ranged from 3 to 19 pCi/L, averaging 10.6 pCi/L over 69 hours.

4 FINAL INSTALLATION

The performance of the temporary system was felt good enough to proceed to a permanent installation and in late May 1988 the temporary exhaust system was removed. A pit similar to a basement window well was excavated to provide space for a fan at grade level, the opening in the wall was enlarged to 10 cm diameter, and a T-2 fan screwed to a sheet of plywood was installed over the opening. The onset of warm weather postponed further radon measurements until Stage 2 of the program.

5 OTHER MEASUREMENTS

The 1987 charcoal canister survey gave a value of 16.4 pCi/L in the hall and bedroom. A short term radon monitor survey in January 1988 found radon concentrations in the bedroom ranged from 13 to 32 pCi/L, averaging 19.6 pCi/L.

A pre-mitigation alpha-track measurement over the period December 1987 to February 1988 gave average radon concentrations of 17.5 pCi/L in the kitchen and 20.9 pCi/L in the bedroom.

A post-mitigation alpha-track measurement over the period May to August 1988 gave an average radon concentration of 9.6 pCi/L in the living area. The owners had turned the fan off at times.

The radiation field in the house ranged from 4 to 6 μR/h in the center of the floor slab to 10 μR/h in contact with the inner surface of the exterior walls. The higher field was due to the radioactivity of the bricks. The field on contact with the outer surface of the walls was 14 μR/h, and an internal fireplace of matching brick also gave 13 μR/h on contact. The field over the site outside the house ranged from 5 to 11 μR/h, averaging 8 μR/h, and a concrete patio gave 6 μR/h.

MEASUREMENTS SUMMARY FOR HOUSE 01

PYLON AB-5 HOURLY MONITORING

MITIGATION SYSTEM	TEST DATE	TEST STATUS	RADON(pCi/L)* RANGE	RADON(pCi/L)* MEAN	MONITOR DURATION*	FIG.
Pre-selection	01/88	central heat pump fan cycling normally (on "automatic")	13-32	19.6	45 hrs	01-1
Pre-mitigation	02/88	h.p. on auto	14-29	21.5	98 hrs	01-2
Sub-slab pressurization by central h.p. fan	02/88	h.p. on continuously	15-27	21.2	56 hrs	01-3
		h.p. on auto	14-23	17.6	37 hrs	01-3
Sub-slab suction (interior pipe, in garage)	03/88	DPmax	4-22	9.9	41 hrs	01-4
		0.5 DPmax	4-31	19.9	36 hrs	01-4
		DPmax	2-23	9.6	98 hrs	01-5
Wall suction (exterior pt.)	04/88	DPmax; h.p. on automatic	1- 8	4.3	49 hrs	01-6
		DPmax; h.p. on continuously	6-15	9.4	38 hrs	01-6
Sub-slab plus wall suction (exterior point)	04/88	DPmax; h.p. auto	0- 3	1.3	24 hrs	01-7
		DPmax; h.p. cont.	3-19	10.6	73 hrs	01-7

Average pre-mitigation Pylon results (presented in Tables IX, X, and 3):
Weighted average of Figures 01-1, 01-2 and the h.p. auto portion of 01-3 (181 hours total) = 20.2 pCi/L.

Average post-mitigation Pylon results:
Central fan on continuously (Table IX) — average of Figure 01-3 (fan on) (55 hours) = 21.2 pCi/L
Sub-slab + block wall suction, central fan cycling (auto), mitigation fan at DPmax (Table X) — average of Figure 01-7 (h.p. auto portion) (24 hours total) = 1.3 pCi/L

* The monitoring duration and the radon concentrations shown in this table generally exclude the first 5 hours of Pylon data collected immediately after a change in system conditions, to account for transition time.

SYSTEMS MEASUREMENTS

PHASE	MITIGATION SYSTEM	TEST DATE	MEASUREMENTS			COMMENT
			SUCTION (Pa)	FLOW (L/s)	RADON (pCi/L)	
1	pre-mitigation	02/88	3100			suction at hole A
			25		45	at hole B
			6500			suction at hole B
			0		15	at hole C
			2500			suction at hole D
			<1			at hole C
			1800			suction at hole E
			6			at hole C
			0			at hole D
					5	rear wall outlet
					5	room air
					8	front wall outlet
1	sub-slab pressurization by central fan		-10*			at hole B
			- 4			at hole C
			-<1			at hole D
			-45			at plenum
1	sub-slab suction (interior pipe)	03/88	320	7	85	sub-slab riser
			150	3		sub-slab riser
1	wall suction (exterior point)	04/88		30	20	at fan
1	sub-slab plus wall suction	04/88		40	12	at fan

* "Negative suction" denotes pressurization relative to house.

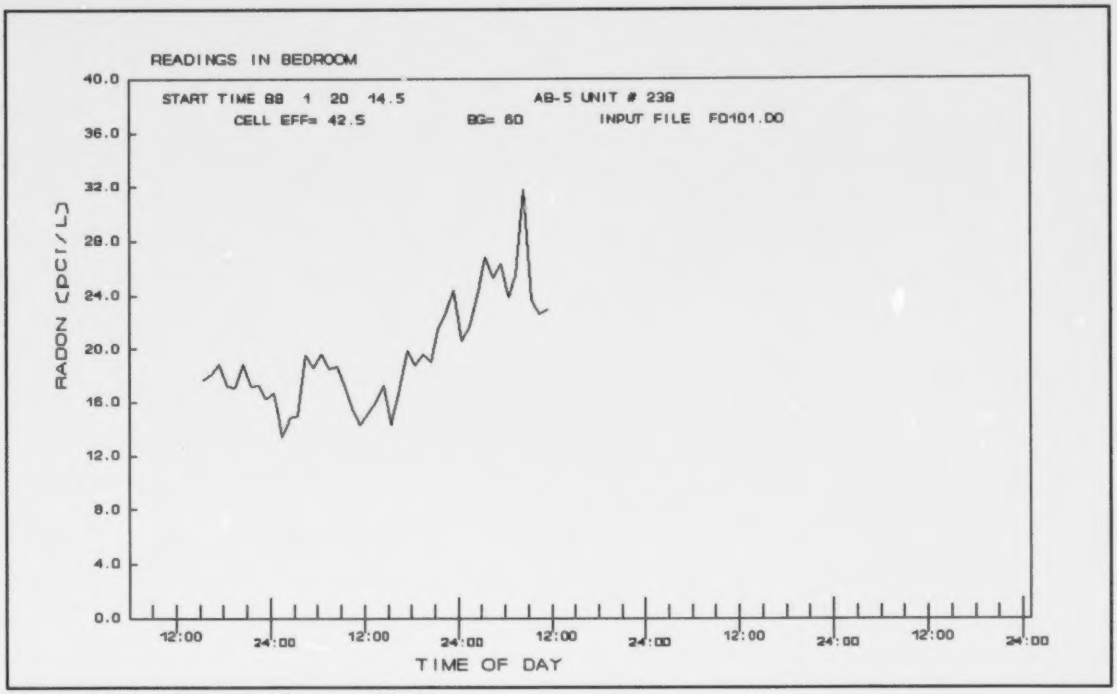


Figure 01-1. Pre-selection monitoring

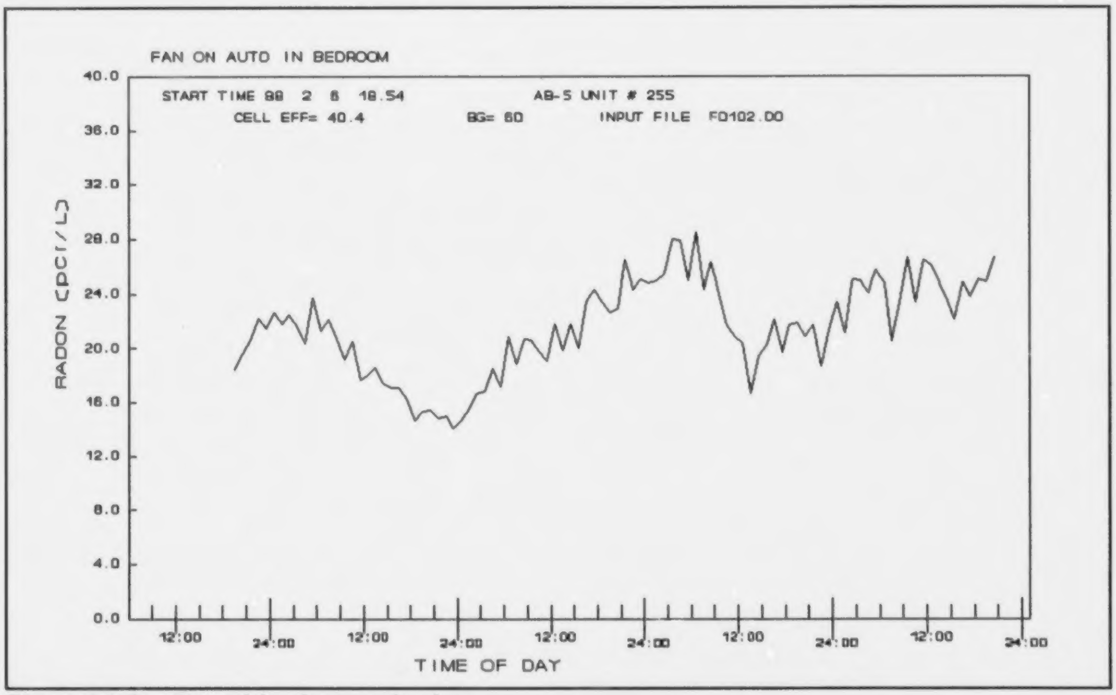


Figure 01-2. Pre-mitigation monitoring

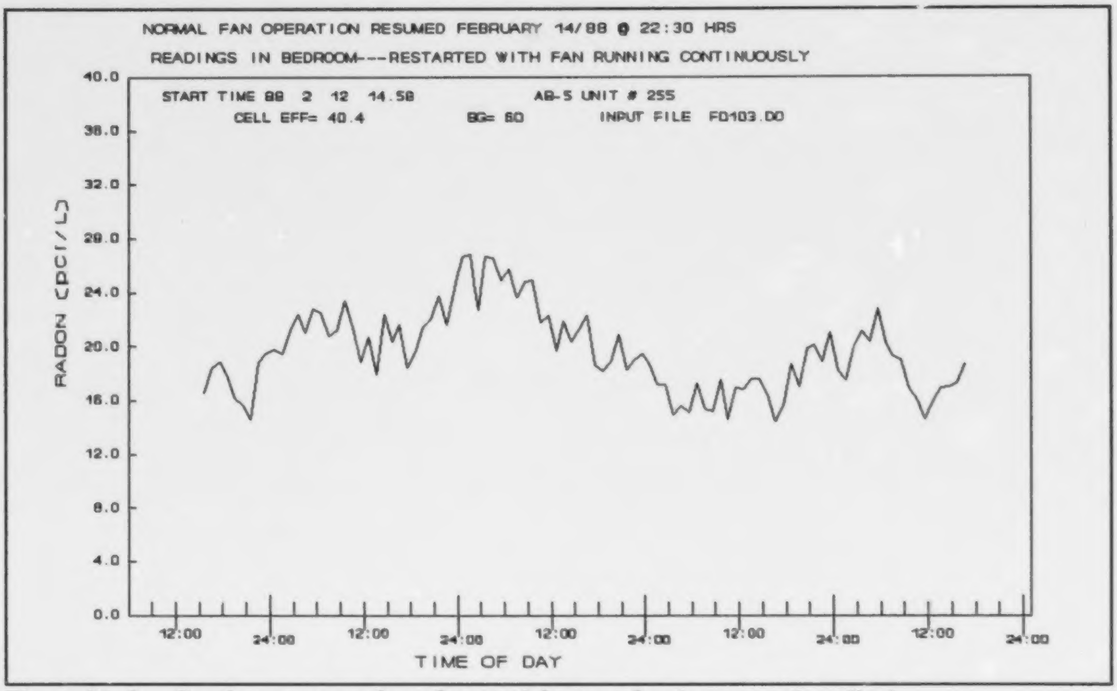


Figure 01-3. Continuous operation of central furnace fan (vs. normal cycling)

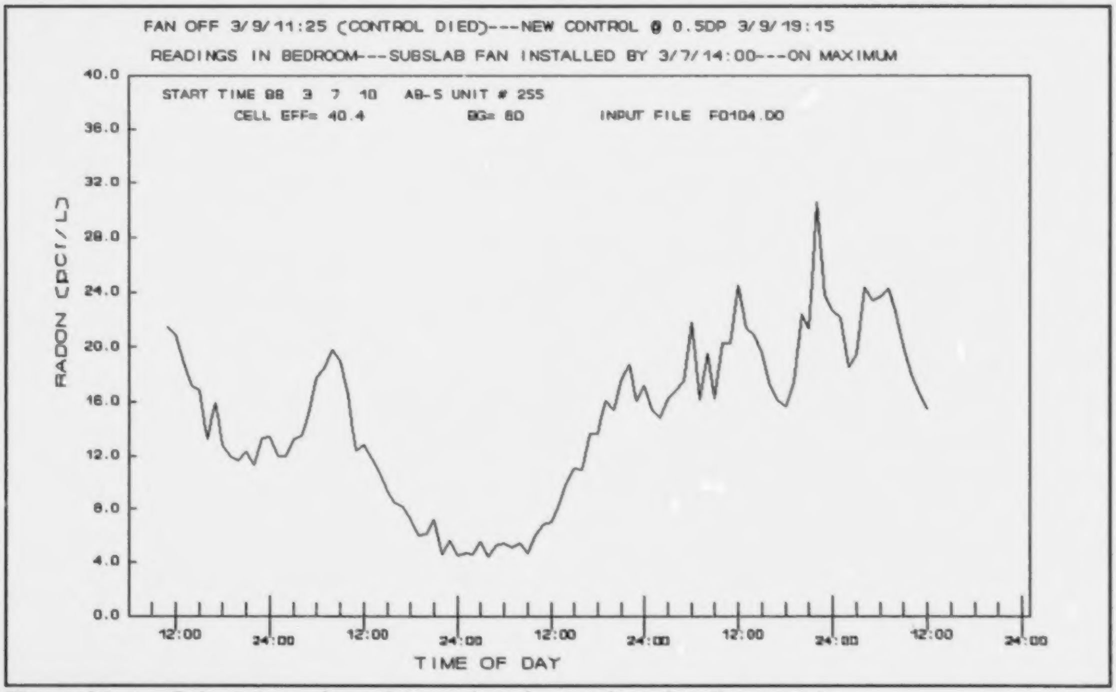


Figure 01-4. Sub-slab suction with one interior suction pipe (in garage)

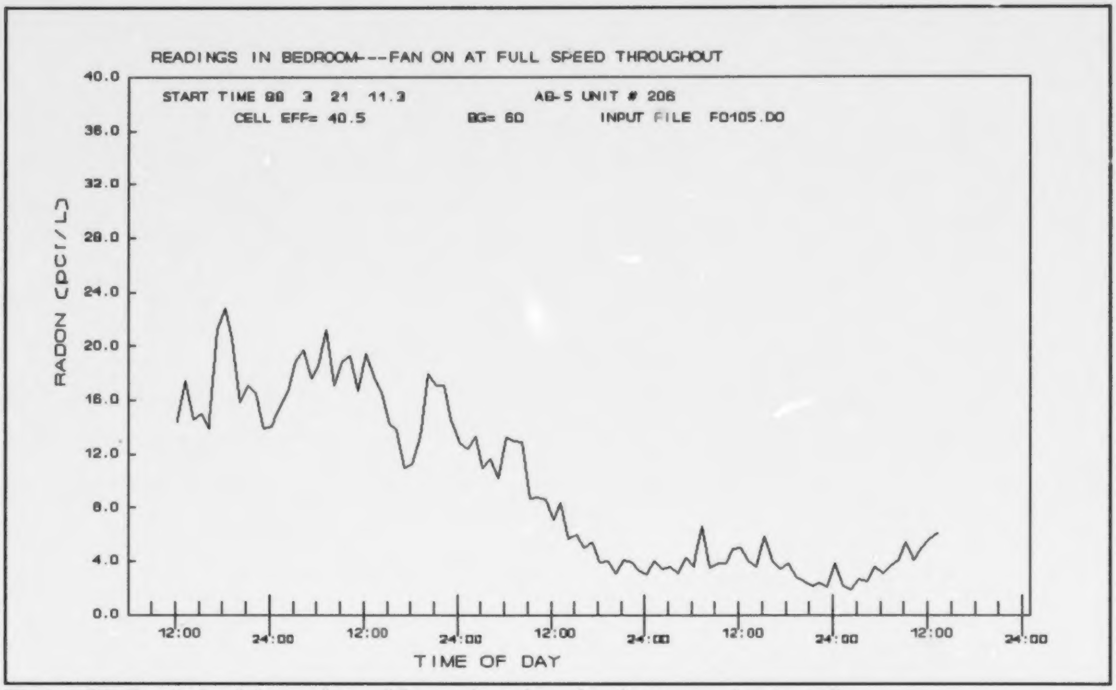


Figure 01-5. Sub-slab suction with one interior pipe in garage (repeated)

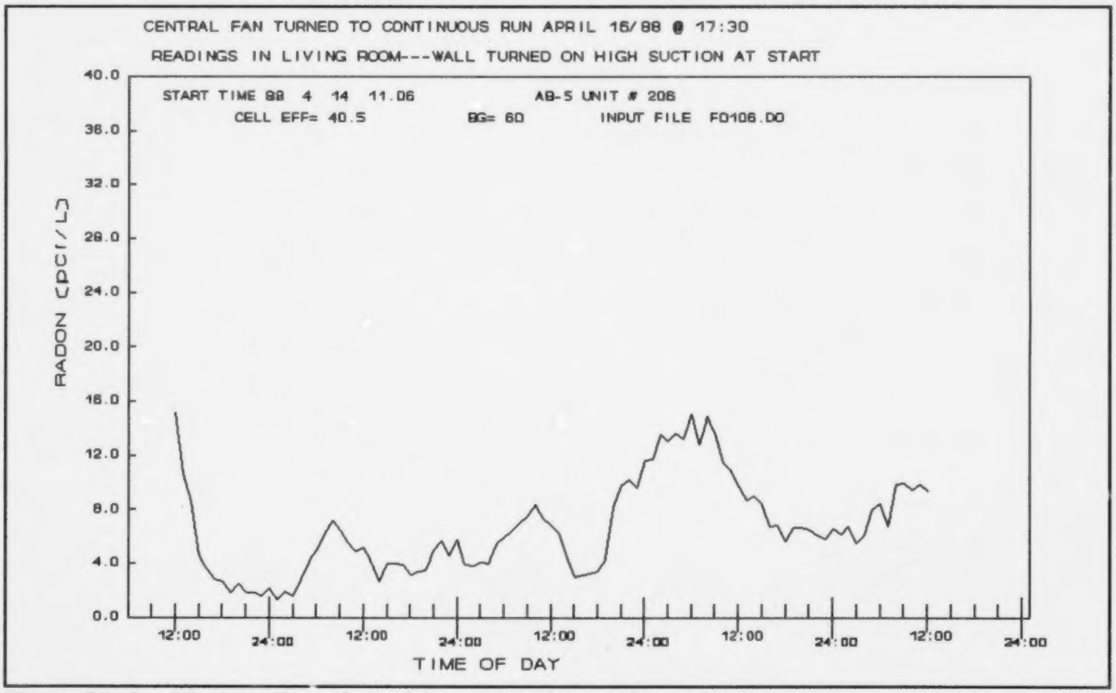


Figure 01-6. Block wall suction with one exterior suction point

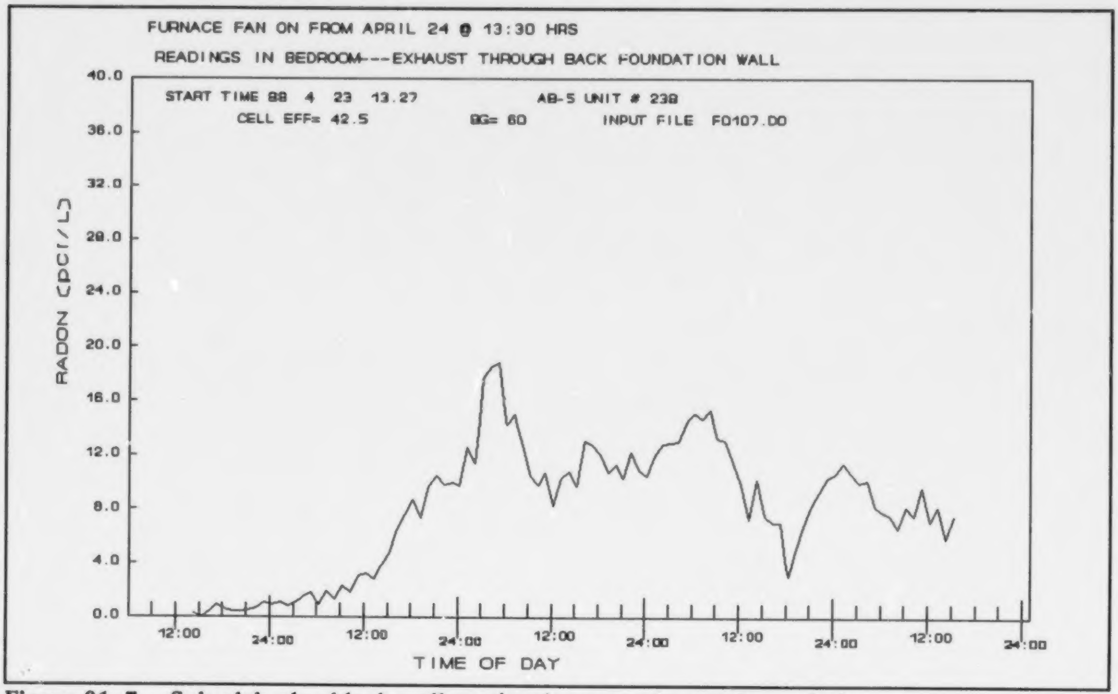
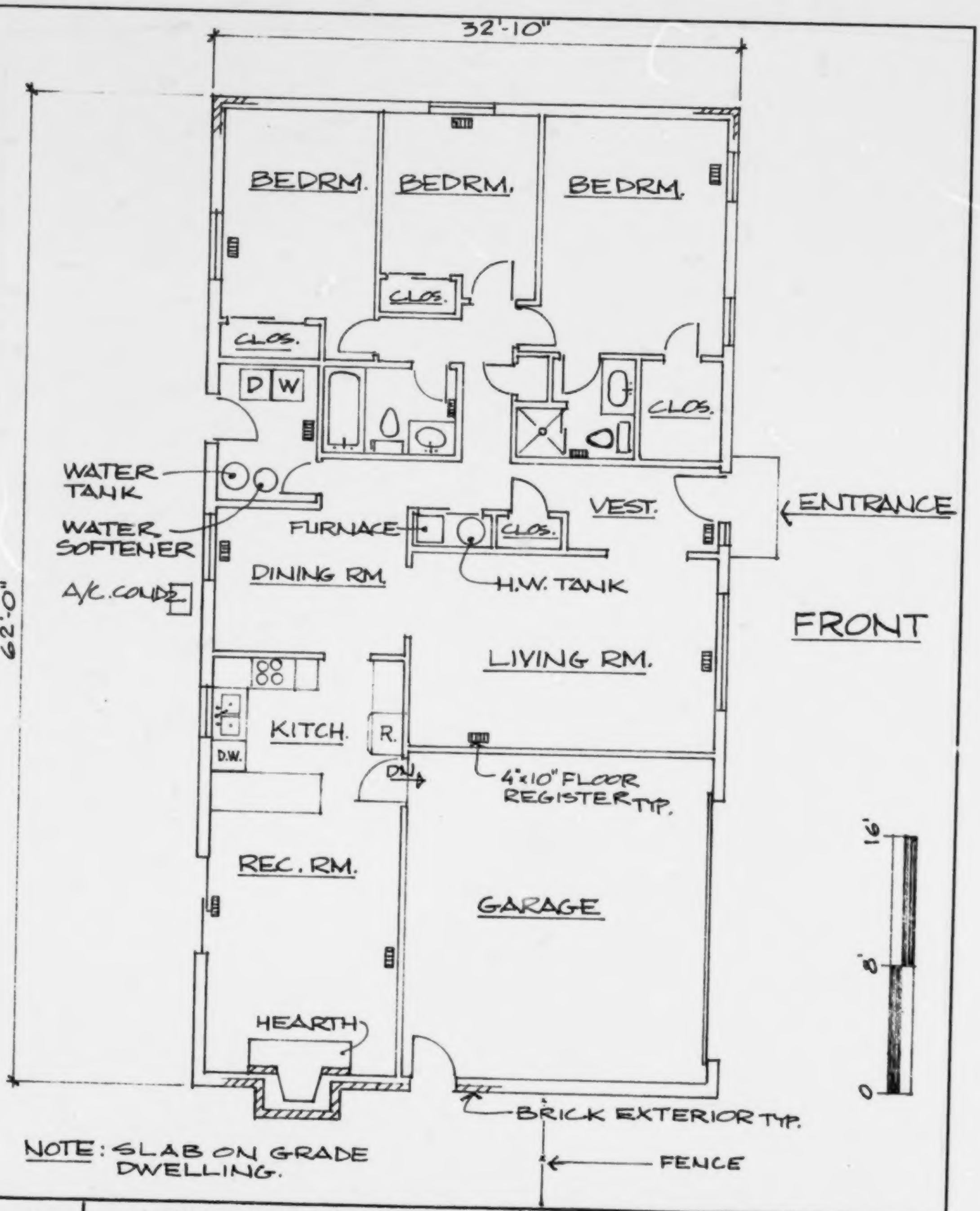
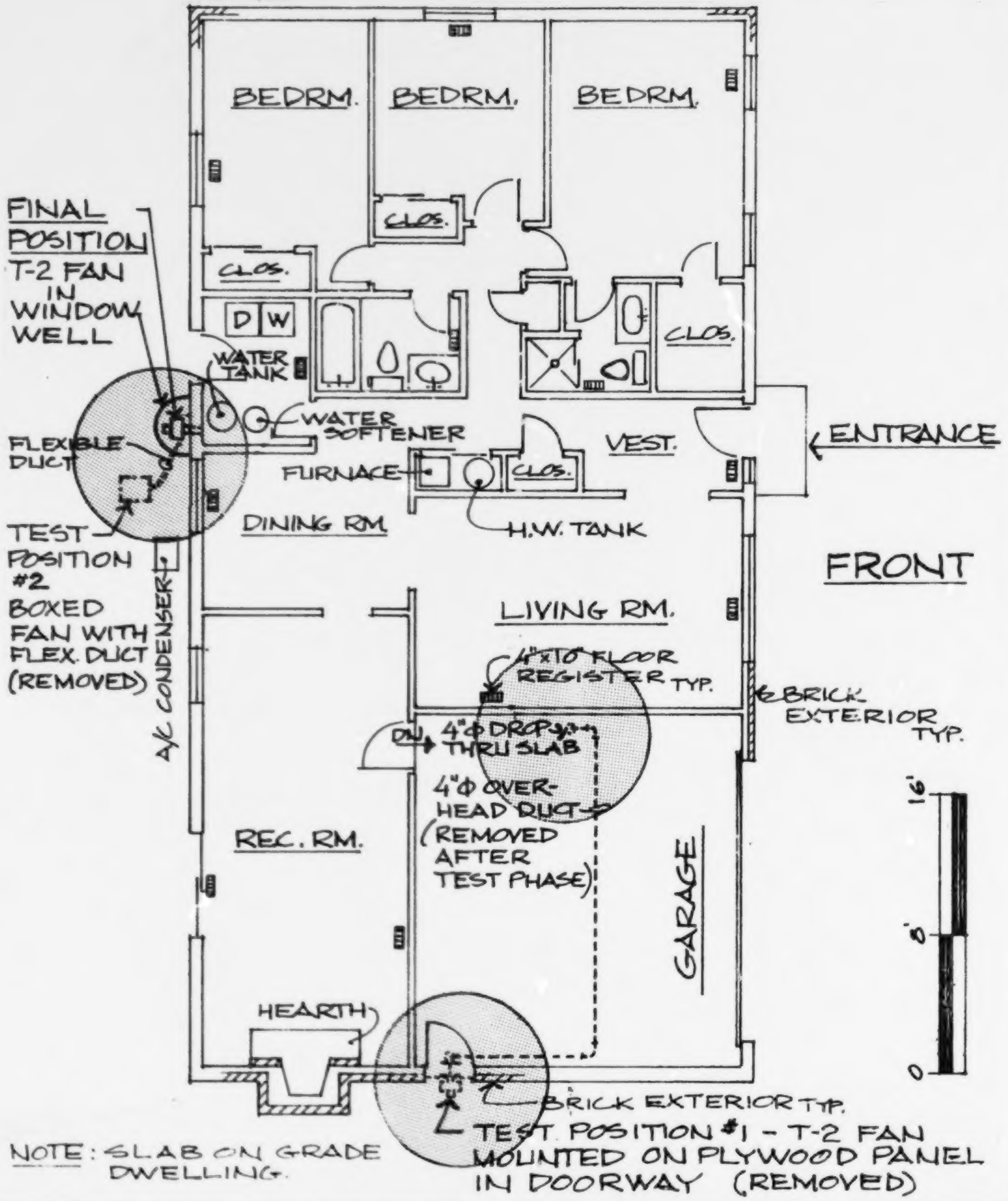


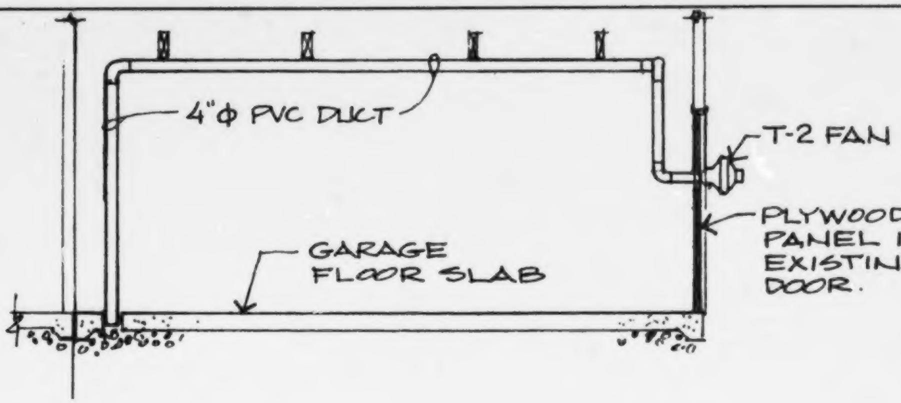
Figure 01-7. Sub-slab plus block wall suction (one exterior suction point)



ACRES Acres International Corporation	LOW COST REDUCTION OF INDOOR RADON	HOUSE NUMBER
	GRADE LEVEL PLAN — Date: 2/22/88	1
	House Group: SLAB ON GRADE — PHASE: —	

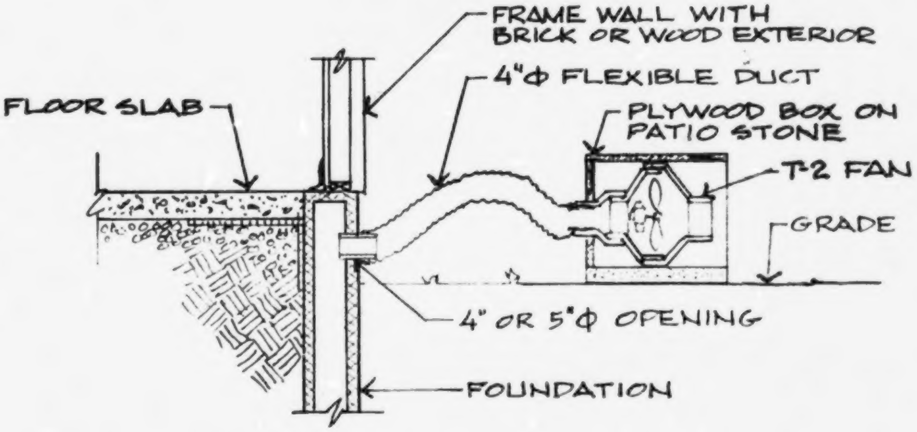


ACRES Acres International Corporation	LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
	GRADE LEVEL PLAN	Date: MAY 1988	1
	Mitigation system: SUB-SLAB SUCTION	PHASE: TEST AND FINAL	



TEST SYSTEM No. 1

N.T.S.

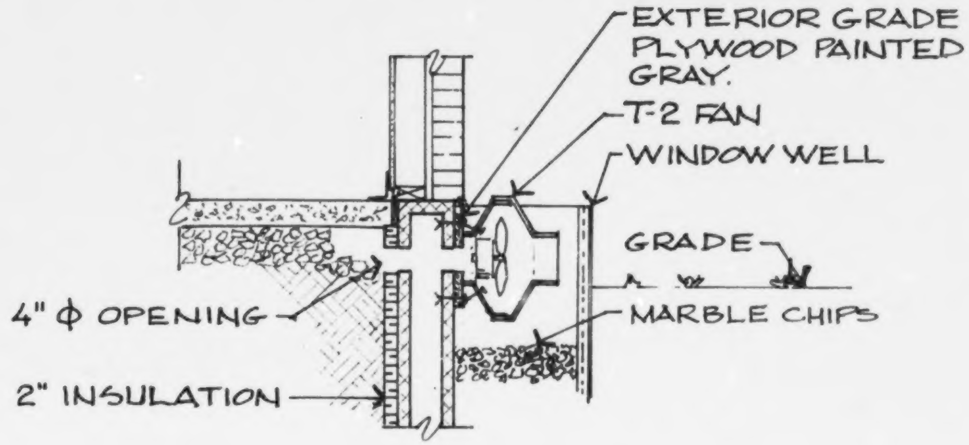


TEST SYSTEM No. 2

N.T.S.

NOTE: ORIGINAL SYSTEM No2 CONFIGURATION SHOWN (BLOCK WALL SUCTION). SYSTEM SUBSEQUENTLY MODIFIED BY PENETRATING INNER FACE OF BLOCK TO PROVIDE SUCTION TO SUB-SLAB FILL.

ACRES Acres International Corporation	**LOW COST REDUCTION OF INDOOR RADON**		HOUSE NUMBER
	SECTIONS/DETAILS	Date: MAY 1988	1
	Mitigation system: SUB-SLAB SUCTION	PHASE: TEST	



FINAL SYSTEM

N.T.S.

ACRES Acres International Corporation	LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
	SECTIONS/DETAILS	Date: MAY 1988	1
	Mitigation system: SUB-SLAB SUCTION	PHASE: FINAL	

HOUSE 04

1 GENERAL DESCRIPTION

This small (90 m^2) single-story basement house with an attached carport was built in the late 1950's in a suburban subdivision in the north of Springfield. The basement foundation wall is of concrete blocks, and has extensive horizontal and vertical cracking. The house exterior walls are of brick. The basement is unfinished with painted walls and a bare concrete floor. Heating is by an upflow forced-air gas furnace with air conditioning located centrally in the basement and metal heat distribution ducts running along the basement ceiling the length of the house. There is a sump at the rear of the basement with a clay crock, one drain pipe entry and a vertical sump pump. It is used as a drain for the washing machine, a dehumidifier, and for the air conditioning condensate discharge.

2 INVESTIGATION

A short-term radon survey was carried out by RAPCA with a "Femtometer" radon monitor as part of the pre-selection process in January 1988. The radon concentration ranged from 25 to 71 pCi/L, averaging 44.3 pCi/L, over 23 hours. A short term Pylon AB-5 survey in February 1988 found that the radon concentration over a 97-hour period was highly variable, ranging from 3 to 247 pCi/L, averaging 40.7 pCi/L.

A sub-slab connectivity test was carried out in February 1988. A 12 mm diameter test hole was drilled in the floor 1.2 m from the sump (A), and a second 12 mm test hole (B) was drilled about 8 m away near the front corner of the house. The radon concentration in the sub slab space was 90 pCi/L at A and 360 pCi/L at B. The sub-slab pressure was about 1 Pa higher than in the house. When a suction of 2500 Pa was applied to hole A, the pressure at B fell 12 Pa, indicating a good sub-slab connection. The building shell differential was 1-2 Pa, measured across a basement window. There was a marked airflow of cool air out of the sump drain tile into the house, with a radon concentration of 45 pCi/L. A plastic garbage can was cut to fit over the sump, and sealed to the floor and piping with expanding foam. The vacuum cleaner was attached to the can, and running at full speed decreased the pressure inside the can by 6 Pa. This reversed the airflow through hole A, indicating good connection between the sump and the subfloor space.

The opening in the can used for the vacuum cleaner nozzle was sealed, and the can left in position to close the sump opening. The radon concentration in the basement for the following 42 hours ranged from 4 to 21 pCi/L, averaging 10.2 pCi/L (see Figure 04-2). Given the high variability in radon concentrations observed in this house, it was not possible to say that closing the sump had in fact significantly reduced the radon supply rate, but it did show that there were other routes of radon entry into the basement besides the sump.

3 MITIGATION

As this house had a sump, the mitigation system selected for demonstration was soil ventilation via the sump and weeping tile. The system was planned in two stages: a temporary system to check the effectiveness of the system, followed by a permanent installation. In early March 1988 a temporary system was installed. It consisted of a plywood cover cut to fit round the pipes into the sump (washer discharge, sump pump pedestal, pump discharge line, and 4-inch exhaust); a temporary floor drain was installed in the cover to handle water on top of the slab. The exhaust pipe was connected to a T-2 fan mounted on a sheet of plywood placed in the nearest basement window. Expanding urethane foam was used to seal around the cover penetrations, and to seal the cover into the sump pit. The pre-mitigation concentrations ranged from 1 to 88 pCi/L, averaging 18.8 pCi/L over a 39 hour period. When the fan was turned on at full speed, the suction in the pipe leading to the fan was 170 Pa, and it withdrew 86 L/s from the sump. The temporary floor drain in the sump cover was a "radon mitigation" drain with a ball to close the trap in the event that the trap dried out. The suction in the sump was greater than the weight of the ball, causing the ball to rise off its seat when the fan was in operation. Thus, the ball feature was not effective in this application, and the trap had to be kept filled with water to prevent the fan from drawing large amounts of air from the house.

Radon concentrations in the basement fell rapidly to range between 0 to 2 pCi/L, averaging 0.8 pCi/L over a 67-hour period (Figure 04-4). The fan speed was then reduced, and the pipe suction decreased to 85 Pa, and the flow to 60 L/s. The concentrations ranged from 0 to 3 pCi/L, averaging 0.8 pCi/L over 65 hours (Figure 04-5, and the 0.5 DPmax portion of Figure 04-4).

As a test of an alternative mitigation strategy, the fan was reversed at reduced speed to pressurize the soil. The pressure in the pipe was 75 Pa, at a flow of 60 L/s. Radon concentrations over a 44-hour period ranged from 1 to 3 pCi/L, averaging 1.7 pCi/L. The pressure in the sub-slab space produced by the fan was measured through the previously drilled test holes. With the fan at reduced speed, pressures were 15 and 12 Pa, and with the fan in suction at reduced speed, the suctions at the holes were 12 and 8 Pa. The fan was returned to maximum suction, 170 Pa in the pipe, producing a flow of 86 L/s.

In early April 1988 the temporary sump ventilation system was replaced by a permanent system. Discussions were held with the owner as to the most acceptable location for the permanent fan, and a location chosen at the rear of the house. The pedestal sump-pump was replaced by a submersible pump, which eliminated the holes in the cover needed for the pedestal and the float-switch control wire. The cover was a lucite disk cut to fit inside the sump lip. Lucite is not affected by moisture, and is transparent so the sump could be inspected without opening the cover. A new washer-discharge pipe containing a water trap was fabricated and passed through the cover, and a standard floor-drain fitting with a deep water trap was placed in the cover to allow the condensate and dehumidifier discharge to drain away. The exhaust pipe ran out through the basement wall above grade, and a Kanalflakt G-1 fan was attached to the wall and to the pipe, discharging at about 300 mm above grade in a flower bed, adjacent to the central air-conditioner compressor unit. A small patch of crushed stone in a wood frame was placed beneath the fan to prevent dusting in dry weather.

The radon concentration in the basement with the permanent system in operation was measured over 95 hours with the fan on high speed. It ranged from 0 to 1 pCi/L, averaging 0.2 pCi/L. The system exhaust flow was 74 L/s, at a concentration of 40 pCi/L. The fan speed was reduced to decrease the fan noise, and the final flow rate was 60 L/s.

4 OTHER MEASUREMENTS

The 1987 charcoal canister test gave a value of 45.9 pCi/L in the basement. A short term radon monitor survey in January 1988 found radon concentrations in the basement ranged from 25 to 71 pCi/L, averaging 44.3 pCi/L.

A pre-mitigation alpha-track measurement over the period December 1987 to February 1988 gave average radon concentrations of 20.7 pCi/L in the living area and 24.5 pCi/L in the basement.

Post-mitigation alpha Track measurements over the period May to August 1988 gave average radon concentrations of 1.4 pCi/L in the living area, and 1.2 pCi/L in the basement.

The radiation field in the basement ranged from 5 to 6 μR/h over the entire floor slab. The field over the site outside the house ranged from 4 to 7 μR/h, averaging 5 μR/h.

MEASUREMENTS SUMMARY FOR HOUSE 04

PYLON AB-5 HOURLY MONITORING

MITIGATION SYSTEM	TEST DATE	TEST STATUS	RADON(pCi/L)* RANGE	MEAN	MONITOR DURATION*	FIG.
pre-selection**	01/88		25- 71	44.3	23 hrs	
pre-mitigation	02/88		3-247	40.7	97 hrs	04-1
temporary cover on sump	02/88	sump closed	4- 21	10.2	42 hrs	04-2
sump suction partly installed (not operating)	03/88	power off from storm	1- 88	18.8	39 hrs	04-3
sump suction	03/88	DPmax	0- 2	0.8	67 hrs	04-4
		0.5DPmax	1- 2	1.4	14 hrs	04-4
		0.5DPmax	0- 3	0.7	51 hrs	04-5
sump pressure	03/88	0.5DPmax	1- 3	1.7	42 hrs	04-5
sump suction (permanent)	04/88	DPmax	0- 1	0.2	95 hrs	04-6

* The monitoring duration and radon concentrations shown in this table generally exclude the first 5 hours of Pylon data collected immediately after a change in system conditions, to account for transition time.

** RAPCA femto-TECH R210F used.

Average pre-mitigation Pylon results in basement (presented in Tables VI, VII, and 3):
Weighted average of pre-selection femto-TECH results and of Figures 04-1 and 04-3 (159 hours total) = 35.8 pCi/L.

Average post-mitigation Pylon results (sump suction with fan at DPmax, presented in Tables VI and VII):
Weighted average of Figures 04-4 (portion at DPmax) and 04-6 (162 hours total) = 0.5 pCi/L.

SYSTEMS MEASUREMENTS

PHASE	MITIGATION SYSTEM	TEST DATE	MEASUREMENTS SUCTION (Pa)	FLOW (L/s)	RADON (pCi/L)	COMMENT
1	pre-mitigation	02/88	1-2			across house shell
			1			across slab
					10	basement air
			2500		90	suction at hole A
			12		360	at hole B
					45	sump drain tile
1	temporary cover on sump	02/88	250			suction at cover
			6		12	in sump
1	sump suction	03/88	170	86		at riser; DPmax
			85	60		at riser; 0.5DPmax
1	sump pressure	03/88	-75*	60		at riser; 0.5DPmax
			-15			at hole A
			-12			at hole B
	sump suction		75	58		at riser; 0.5DPmax
			12			at hole A
			8			at hole B
			170	86		at riser; DPmax
1	sump suction (permanent)	04/88	170	74	40	at riser; DPmax

* "Negative suction" denotes pressurization relative to house.

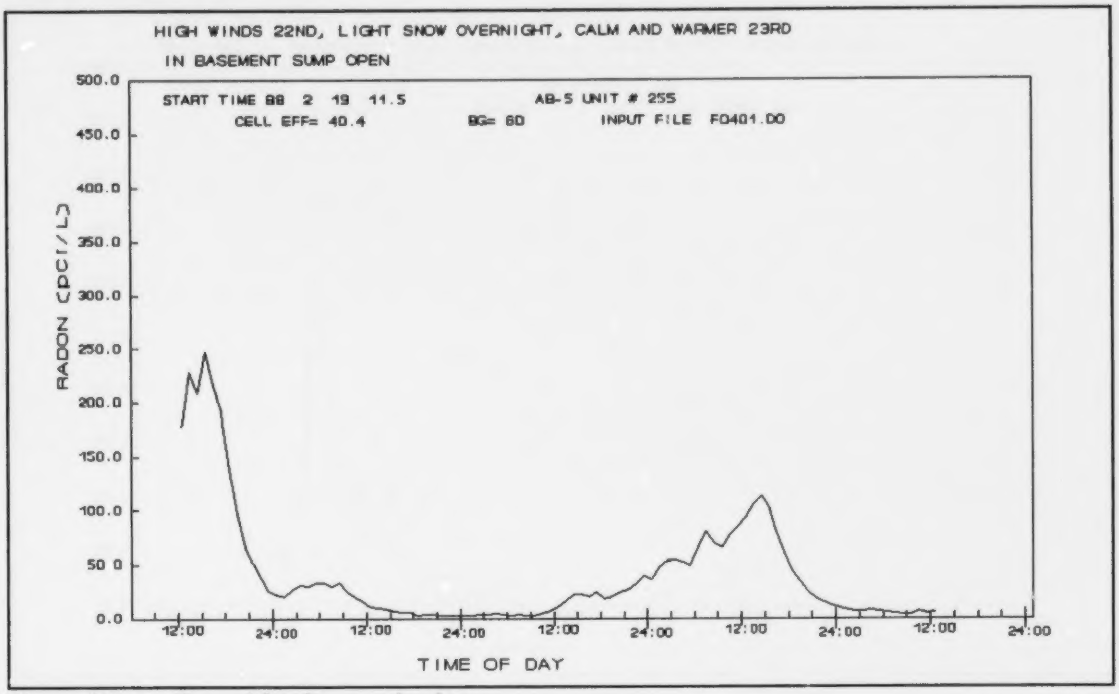


Figure 04-1. Pre-mitigation monitoring

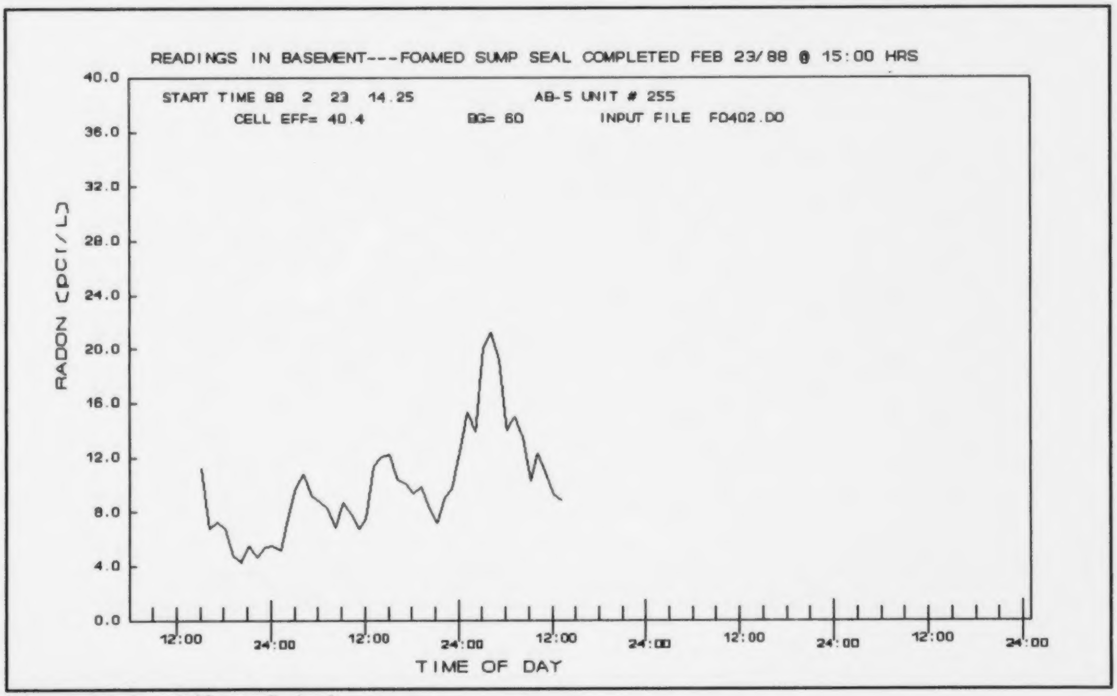


Figure 04-2. Effect of closing sump

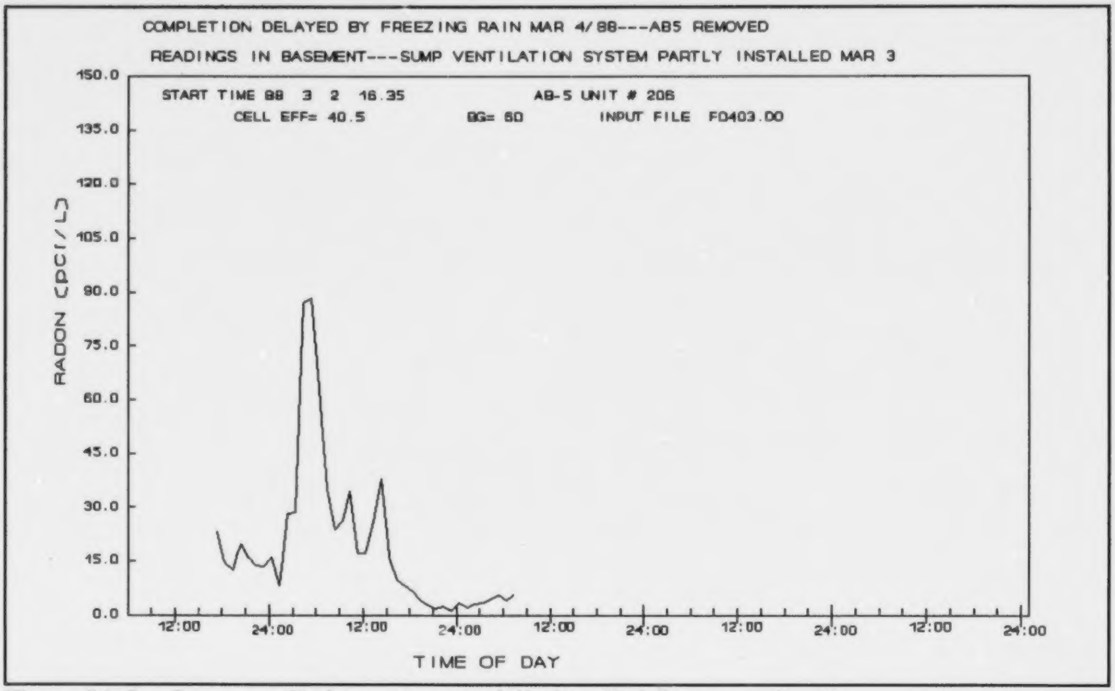


Figure 04-3. Sump ventilation system partially installed (not operational)

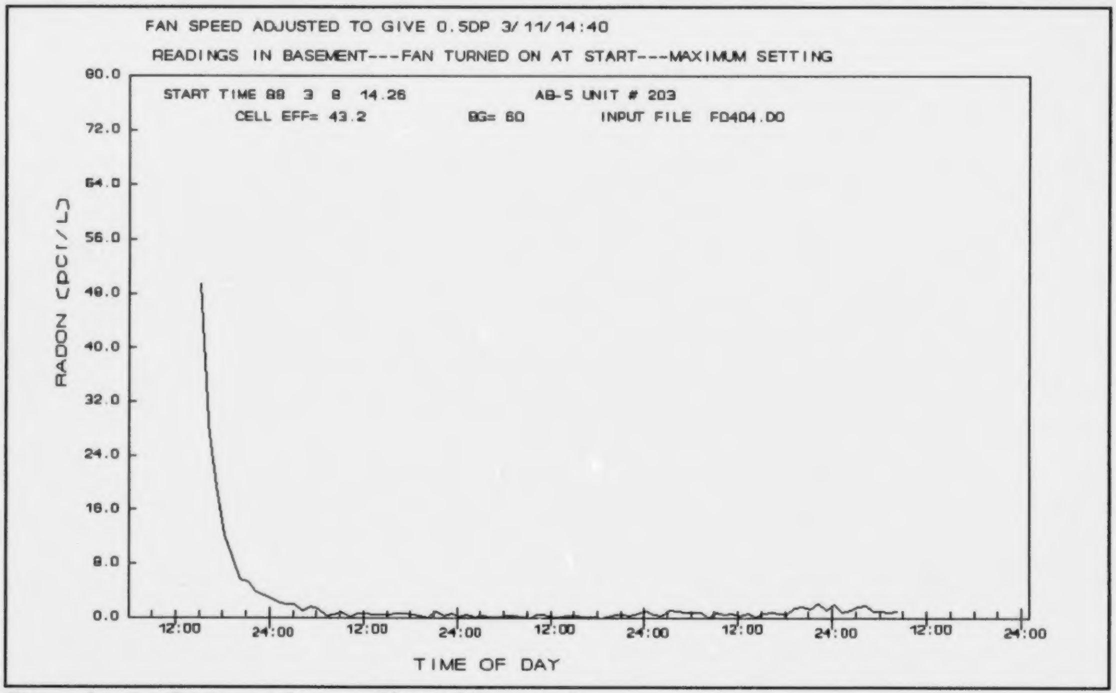


Figure 04-4. Sump suction -- effect of fan speed

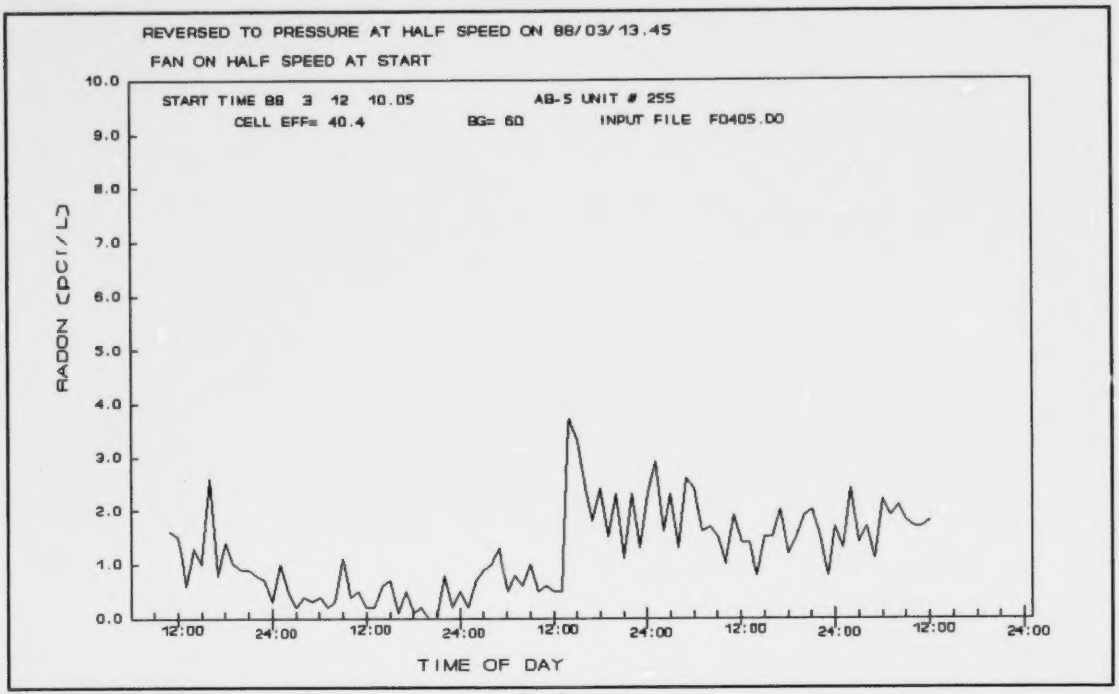


Figure 04-5. Sump suction vs. sump pressurization

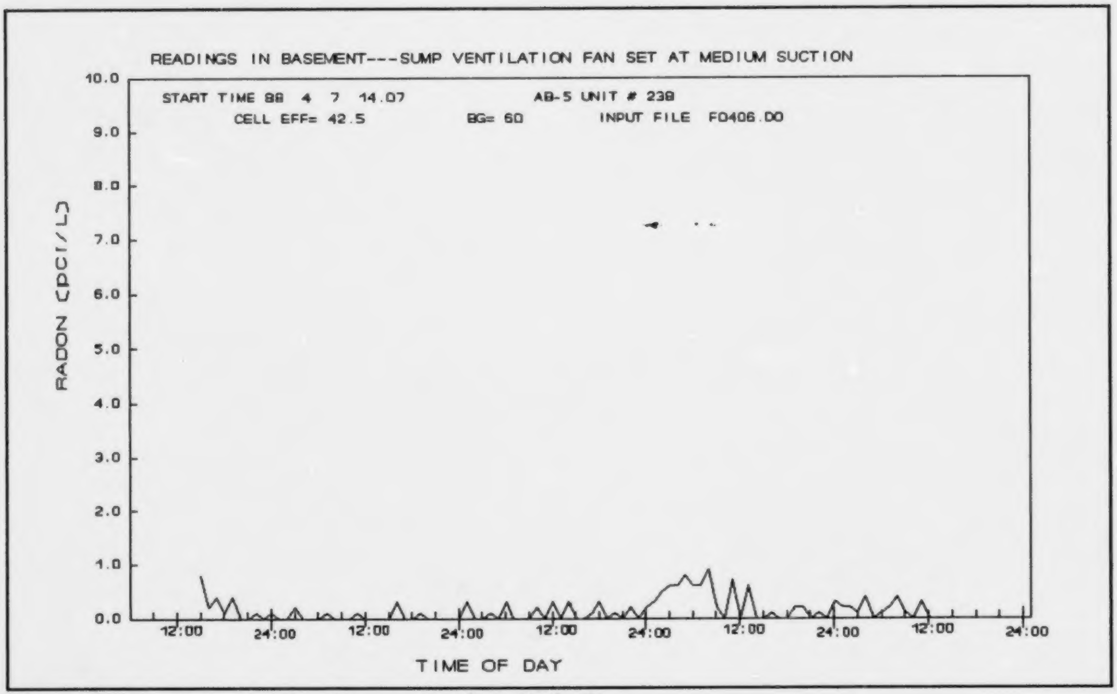
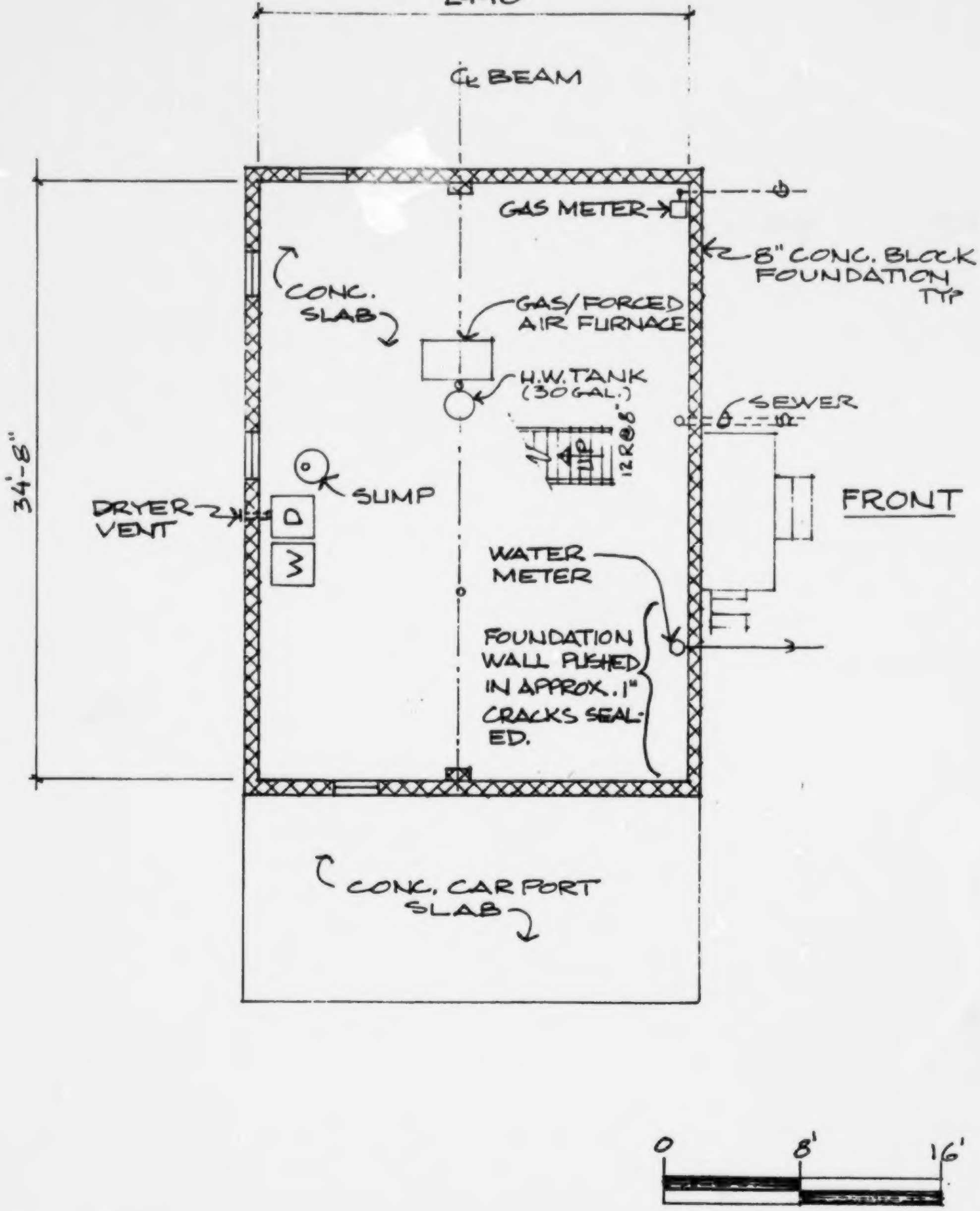
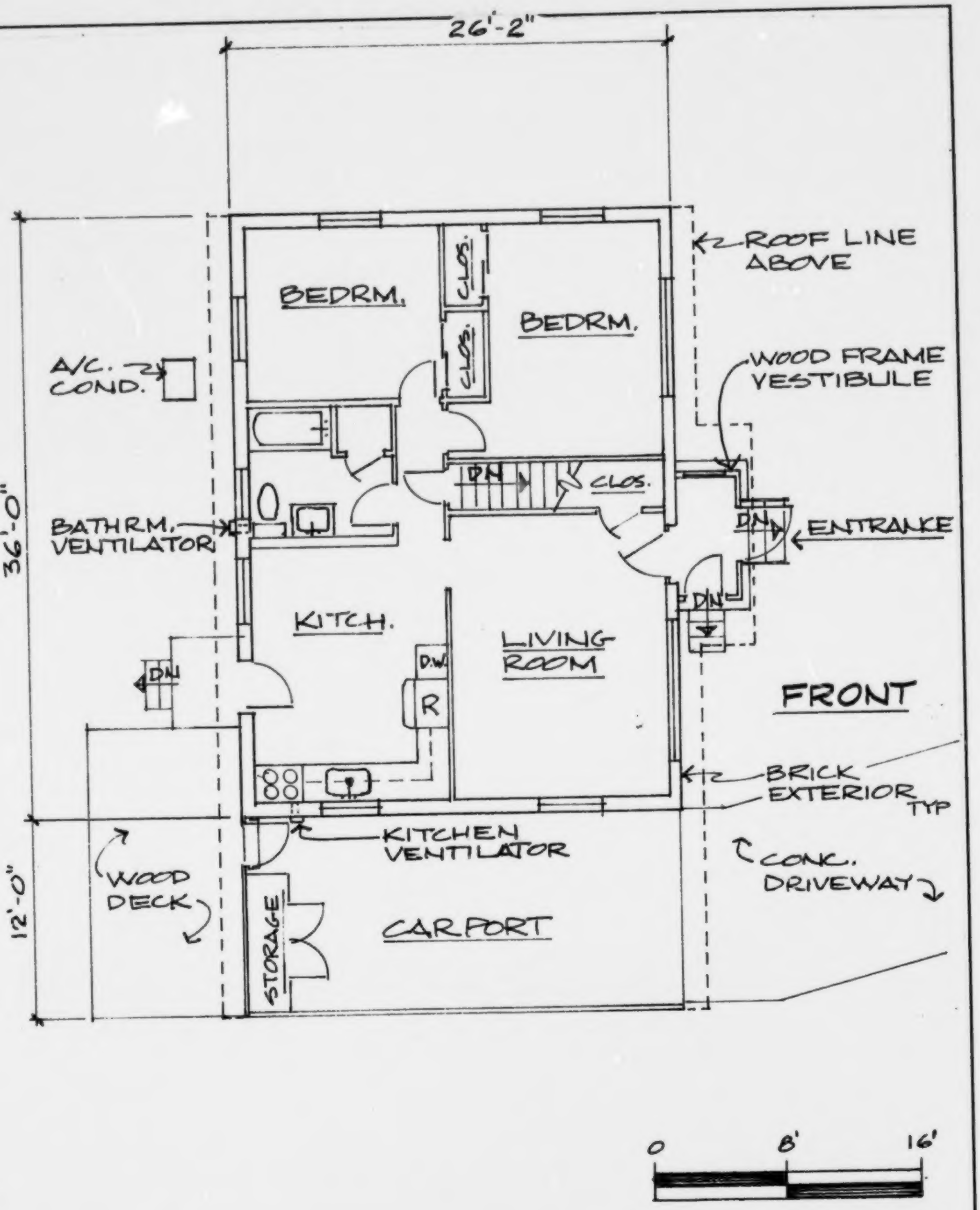


Figure 04-6. Sump suction (permanent installation)



ACRES Acres International Corporation	LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
	BASEMENT/FOUNDATION PLAN	Date: 2/26/88	4
	House Group: **FULL BASEMENT**	PHASE: —	



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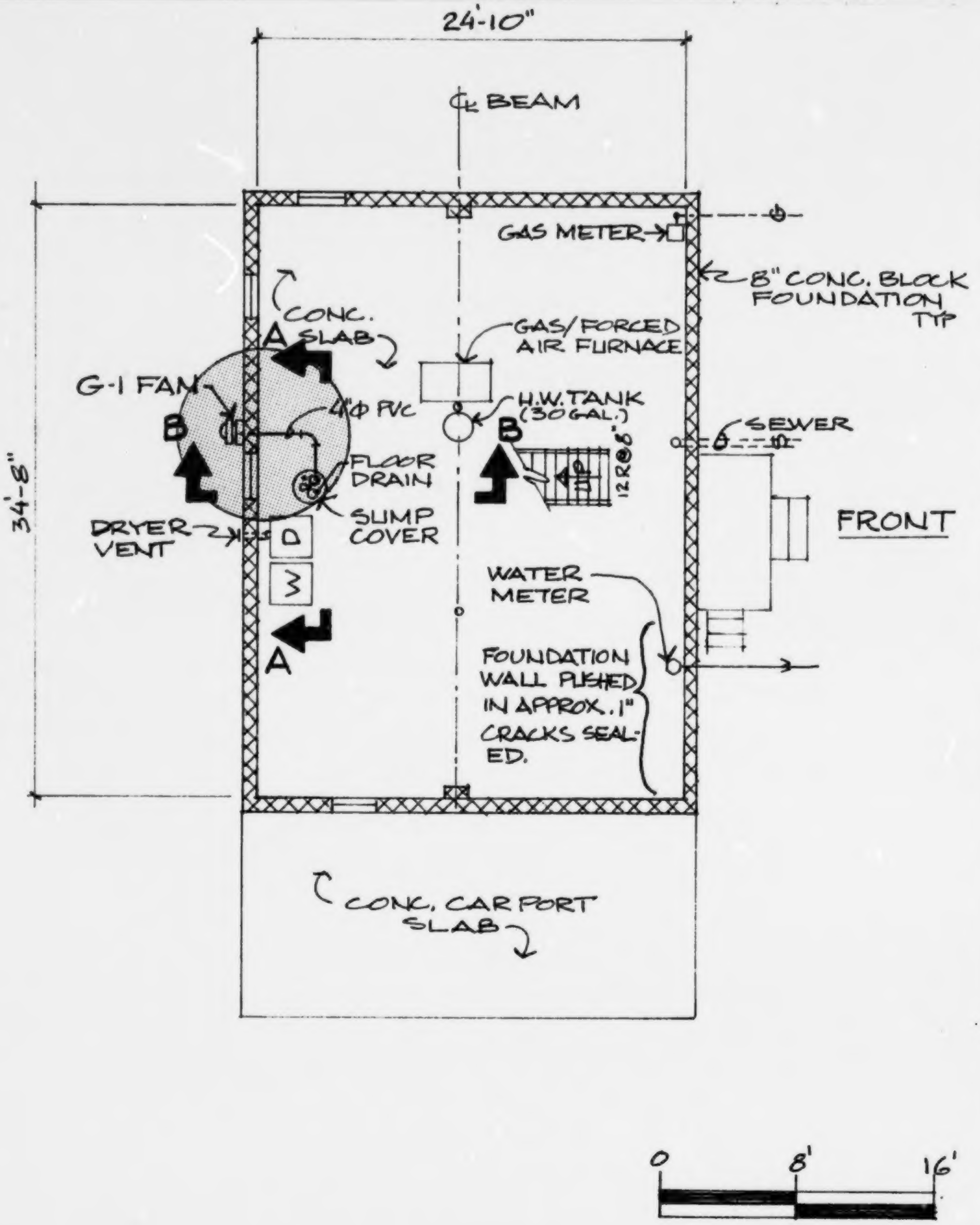
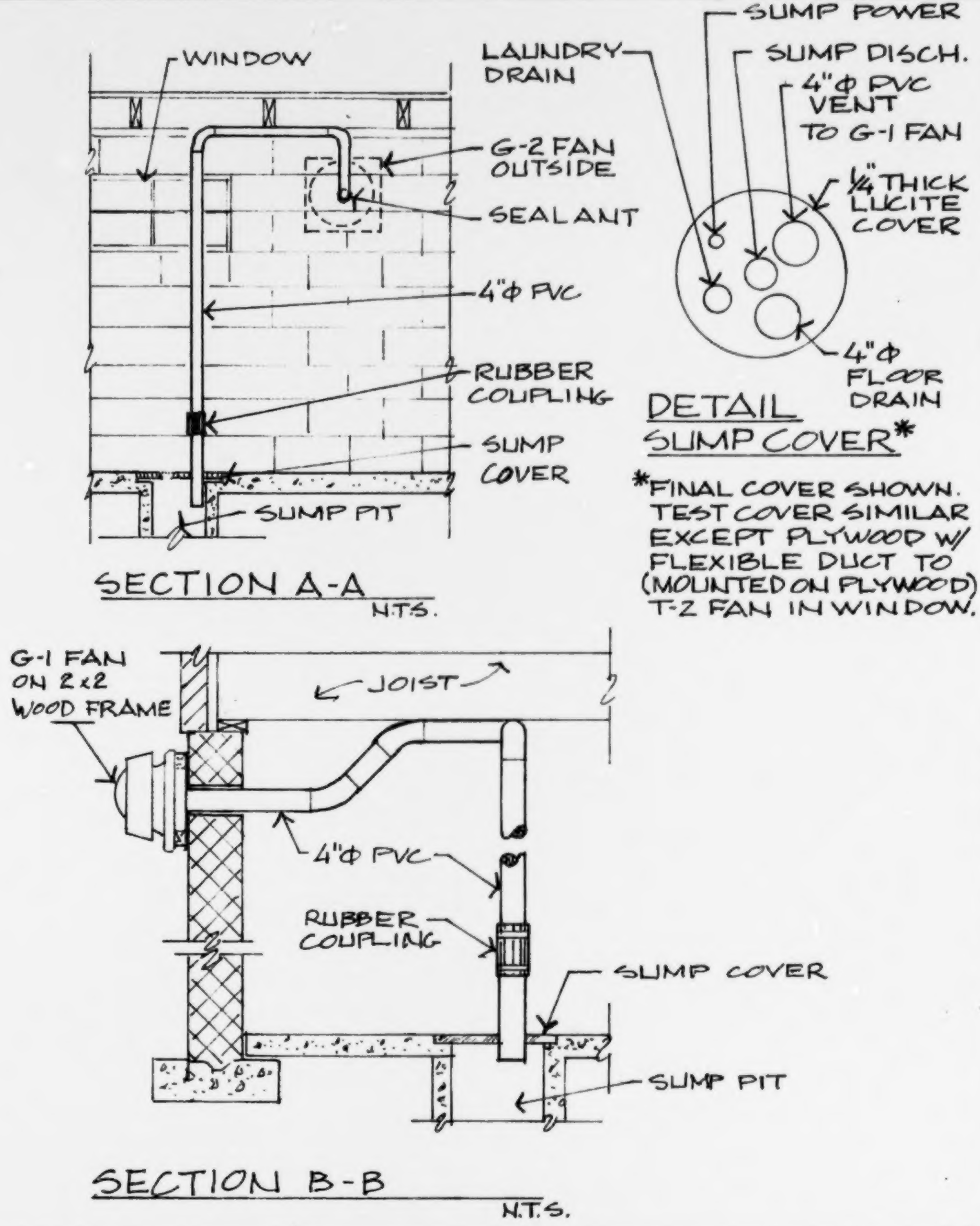
LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
GRADE LEVEL PLAN	Date: 2/26/88	4
House Group: FULL BASEMENT	PHASE: —	



ACRES Acres International Corporation	LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
	BASEMENT/FOUNDATION PLAN	Date: MAY 1988	4
	Mitigation system: SUMP SUCTION	PHASE: FINAL	



LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
SECTIONS/DETAILS	Date: MAY 1988	4
Mitigation system: SUMP SUCTION	PHASE: FINAL	

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HOUSE 07

1 GENERAL DESCRIPTION

This small (110 m^2) single-story basement house with an attached garage was built in the early 1960's in a large rural subdivision to the north of Springfield. The basement foundation wall is of poured concrete, and the exterior walls are of brick. Most of the basement is finished with paneling, a plaster finished ceiling, floor tile and fitted carpet, and contains a recreation and sitting room and a separate study. The concrete floor is exposed only in the laundry room and work shop/storage area located at the rear of the basement, and is extensively cracked in that area. Heating is by an upflow forced-air electric furnace with air conditioning located in the laundry room and heat distribution ducts running the length of the house in a box along the recreation room ceiling. The water softener and the air conditioning condensate discharge to a trapped floor drain.

2 INVESTIGATION

In early January 1988 this house had an EPA pre-selection visit during which a sub-slab permeability and connectivity test was carried out. A 30 mm hole was drilled centrally in the workroom near the furnace, and 12 mm test holes were drilled at distances of 0.3 m (hole A), 3 m in one direction (hole B), and 4 m in the other direction (hole C) from the 30 mm hole. The sub-slab fill was visible through the 30 mm hole, and appeared to be a pea-gravel. When 2000 Pa suction was applied to the large hole, the suctions measured at the other holes were A=275 Pa; B=55 Pa; C=48 Pa, for a near/far pressure ratio of 275/48 = 5.5. This is an indicator of good permeability, and the similar values obtained in different holes suggested the fill was uniform. The sub-slab radon concentration was measured immediately the holes were drilled, and was 870 pCi/L through the large hole, and 1200 pCi/L through hole C. The basement air concentration at the same time was 20 pCi/L, and 35 pCi/L was measured in a trapped floor drain.

The owner said that there had been a 'french drain' — an opening between the poured concrete wall and the floor-slab — but he had filled this with expanding urethane foam before he had finished the walls. He had also filled most of the cracks in the floor with silicone caulk when he had discovered that radon concentrations were elevated.

In early January 1988 a short-term radon-monitor measurement in the basement found that over 70 hours the concentration ranged from 4 to 23 pCi/L, averaging 11.9 pCi/L. In late February 1988, a second monitor run found that the radon concentration varied from 2 to 29 pCi/L, averaging 10.1 pCi/L over 94 hours.

3 MITIGATION

As this house had good sub-slab connectivity, the floor was extensively cracked, and the wall/floor joint was generally inaccessible, sealing was not a valid option. The mitigation system chosen for demonstration was sub-slab ventilation. The system was planned in two stages, a temporary system to verify the design would work, and then a permanent system. The proposed temporary system was a single point exhaust located in the workroom on the centerline of the house, close to the recreation room dividing wall. This would be connected to a Kanalflakt T-2 fan mounted on a sheet of plywood placed in a basement window. Discussion with the owner resulted in relocation of the exhaust point from one side of the workroom door beside the recreation room dividing wall to the other side of the door close to the furnace. The permanent installation would use the same floor exhaust point, but the exhaust duct would be routed up through a closet to the attic space, and from there to a T-2 fan mounted in the garage attic, well away from the sleeping quarters.

The temporary system was installed in early March 1988, and with the fan operating at full speed, radon concentrations over 91 hours ranged from 1 to 6 pCi/L, averaging 2.6 pCi/L (see Figure 07-3). The suction in the exhaust pipe was 350 Pa, at a flow of 2 L/s. The fan was turned on as soon as the installation was completed, and the suction was so high that the acrylic caulking used to seal the seam where the PVC pipe penetrated the concrete slab was drawn down the space between the pipe and the slab before it set, leaving an opening between the slab and the pipe. This was detected by the noise made by the air whistling through the hole. The owner stopped the air-flow by re-caulking. The radon concentration in the exhaust air was 630 pCi/L.

The air-flow in the system was very low considering the indications of good sub-slab connectivity given by the pre-selection test. The original test holes were drilled open, and the suction under the slab produced by the fan was measured for a direct comparison of sub-slab suctions produced by the mitigation system vs. suctions produced by the industrial vacuum cleaner. At hole B, the pressure drop varied between 4 to 6 Pa, probably the result of wind pressures, and at hole C, it varied between 4 to 5 Pa.

The fan speed was reduced so that the suction in the pipe decreased to 160 Pa, and the flow fell 1 L/s. This reduced the pressure drop at the test holes to about 2 Pa, but there was occasional flow reversal at hole B, as shown by a smoke test. The fan was left running at the lower speed, and the radon concentration in the basement after this change ranged from 1 to 6 pCi/L over 93 hours, averaging 2.2 pCi/L.

At the end of this run, as a test of soil ventilation by pressure, the fan was reversed, still at low speed. The pressure in the pipe was 280 Pa, and the flow was 1 L/s. During the 89 hours following this change (after a 5-hour transition period), radon concentrations ranged from 3 to 12 pCi/L, averaging 5.8 pCi/L.

The fan was returned to suction at high speed (310 Pa). Additional test holes (holes 2 - 7) were drilled between the exhaust pipe and test hole B to measure the change of pressure with distance. The suction under the slab at hole B was only about 1 Pa, and hole 2, at 1.5 m towards the exhaust pipe, gave 2 Pa. Hole 3, a further 1.5 m towards the exhaust pipe, gave 4 Pa. At hole 4, 60 cm nearer the pipe across a filled floor crack gave 15 Pa. This hole was 80 cm from the pipe in the direction of hole B. The suction produced in the original 30 mm test hole (1 m from the pipe, now called hole 7) was 30 Pa, and in hole 5, 60 cm away across a crack, it was 23 Pa. At hole 6, drilled 0.3 m from the suction pipe, the sub-slab suction was >120 Pa. The near/far ratio from these holes was 120 Pa/1 to 2 Pa = 60 to 120; this is so different from the pre-selection diagnostic test value of 5.5 to suggest that either the higher test suctions caused an overestimate of the permeability, or there had been a genuine change in conditions with time.

Probes down the holes found that the sub slab fill had a large component of fine material, and was not a clear pea-gravel, as had been thought at the time of the tests. This was confirmed when the final system was installed. A sample of the sub-slab material was taken through the hole cut for the pipe. The upper surface of the material was comprised of small pebbles in the 5 mm size range, and appeared to be a pea-gravel, but the bulk of the material was a pit run sandy gravel with stones as large as 6 cm diameter. Probably leveling the fill had brought the coarser material to the surface, giving it the appearance of a pea-gravel when examined through the test hole.

4 FINAL INSTALLATION

In early April 1988, the final system was installed. The temporary system was removed, and the gravel fill removed from beneath the opening in the floor. A 4-inch pipe was run from the existing opening in the floor vertically from the basement to the attic through the bathroom service chase. The pipe then ran through the trusses to the garage attic space, where a T-2 fan was mounted vertically between two rubber couplers, and discharged via a 4" pipe through the garage roof. The new installation gave 320 Pa suction at the floor, and a flow of 2.1 L/s. The radon concentration in the exhaust was 750 pCi/L. Radon concentrations in the basement with this system in operation ranged from 0 to 2 pCi/L and averaged 1.4 pCi/L over 81 hours (Figure 07-6).

5 OTHER MEASUREMENTS

The 1987 charcoal canister test gave a reading of 25.8 pCi/L in the basement. A short-term radon-monitor survey found concentrations over 4 days ranged from 4 to 23 pCi/L, averaging 11.9 pCi/L.

A pre-mitigation alpha-track measurement over the period December 1987 to February 1988 gave average radon concentrations of 9.5 pCi/L in the kitchen and 10.1 pCi/L in the basement.

A post-mitigation alpha-track measurement over the period May to August 1988 gave an average radon concentrations of 1.1 pCi/L in the living area, and 2.0 pCi/L in the basement.

The radiation field in the basement ranged from 4 to 5 μR/h over the entire floor slab. The field over the site outside the house ranged from 7 to 9 μR/h, averaging 8 μR/h.

MEASUREMENTS SUMMARY FOR HOUSE 07

PYLON AB-5 HOURLY MONITORING

MITIGATION SYSTEM	TEST DATE	TEST STATUS	RADON (pCi/L)* RANGE	MEAN	MONITOR DURATION*	FIG.
pre-selection	01/88		4-23	11.9	70 hrs	07-1
pre-mitigation	02/88		1-29	10.1	94 hrs	07-2
sub-slab suction	03/88	DPmax	1- 6	2.6	91 hrs	07-3
		0.5DPmax	1- 6	2.2	93 hrs	07-4
sub-slab pressure	03/88	Reduced fan speed	3-12	5.8	89 hrs	07-5
sub-slab suction (permanent)	04/88	DPmax	0- 2	1.4	67 hrs	07-6

* The monitoring duration and radon concentrations shown in this table generally exclude the first 5 hours of Pylon data collected immediately after a change in system conditions, to account for transition time.

Average pre-mitigation Pylon results (presented in Tables IV and 3):

Weighted average of Figures 07-1 and 07-2 (164 hours total) = 10.9 pCi/L.

Average post-mitigation Pylon results (sub-slab suction with fan at DPmax, presented in Table IV):

Average of Figure 07-3 (91 hours total) = 2.6 pCi/L.
(Figure 07-6 is not included in the calculation here because that measurement was completed in late April, after weather had turned mild.)

SYSTEMS MEASUREMENTS

PHASE	MITIGATION SYSTEM	TEST DATE	MEASUREMENTS SUCTION (Pa)	FLOW (L/s)	RADON (pCi/L)	COMMENT
1	pre-selection	01/88	2000		870	suction at slab
			275			at hole A
			55			at hole B
			48		1200	at hole C
					35	floor drain
					20	basement air
1	sub-slab suction	03/88	350	2	630	at riser; DPmax
			4-6			at hole B
			4-5			at hole C
			160	1		at riser; 0.5DPmax
			2			at hole B
			2			at hole C
1	sub-slab pressure	03/88	-280*	1		reduced speed
1	sub-slab suction	03/88	310			at riser; DPmax
			1			at hole B
			2			at hole 2
			4			at hole 3
			15			at hole 4
			23			at hole 5
			>120			at hole 6
			30			at hole 7
1	sub-slab suction (permanent)	04/88			750	at riser; fan off
			320	2	760	at riser; DPmax

* "Negative suction" denotes pressure in pipe greater than pressure in house.

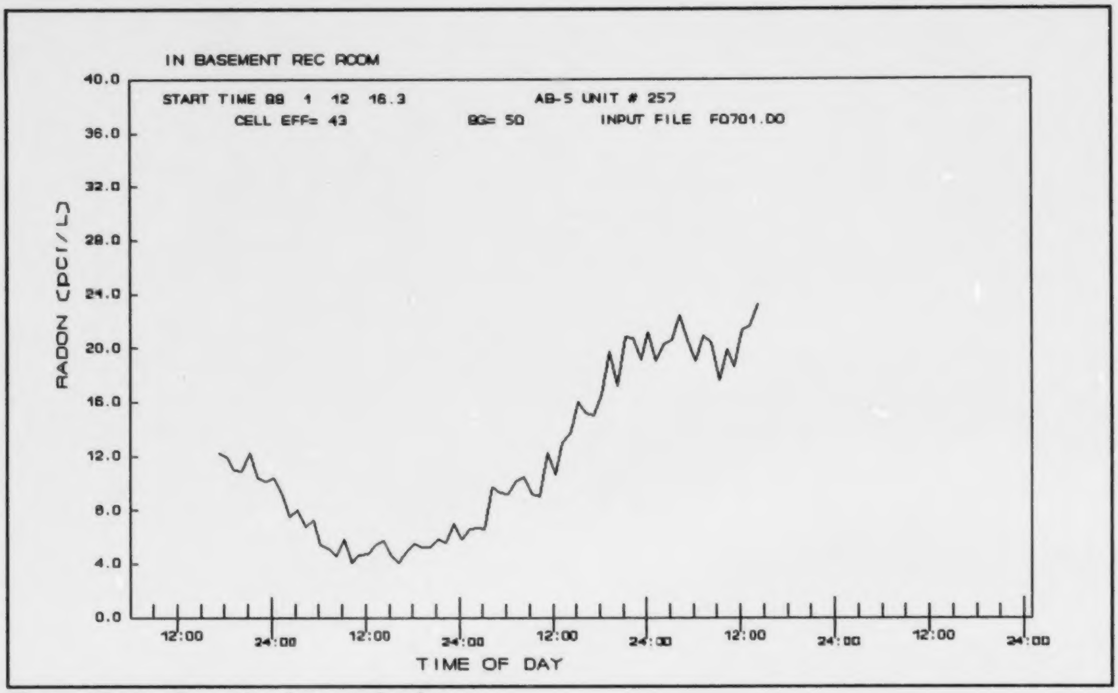


Figure 07-1. Pre-selection monitoring

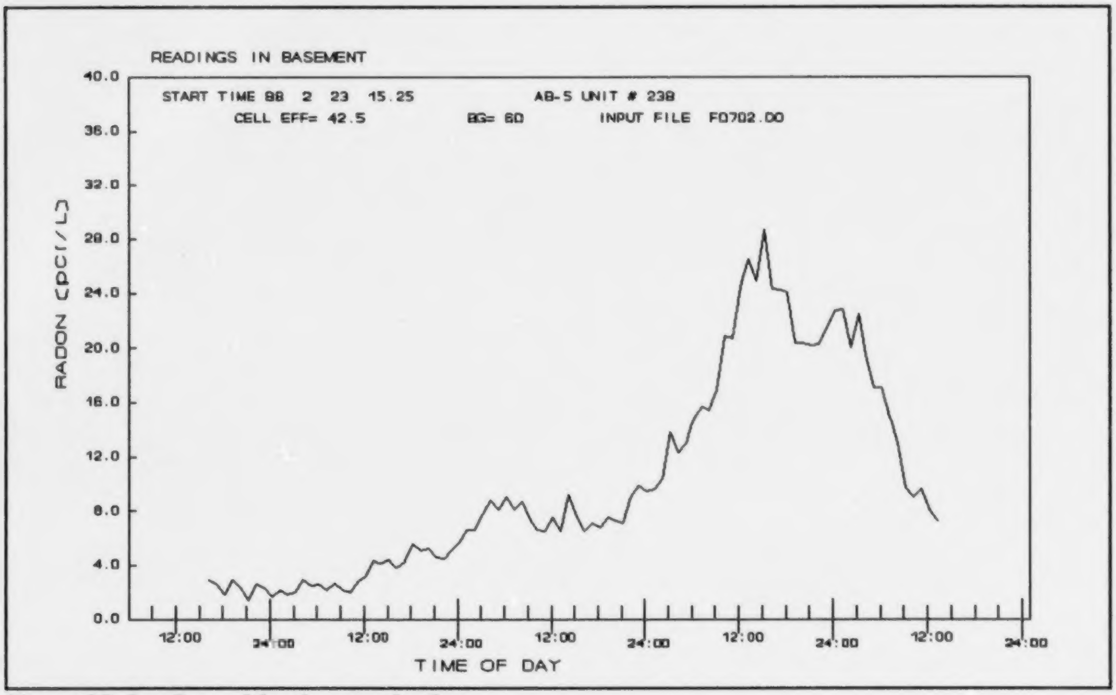


Figure 07-2. Pre-mitigation monitoring

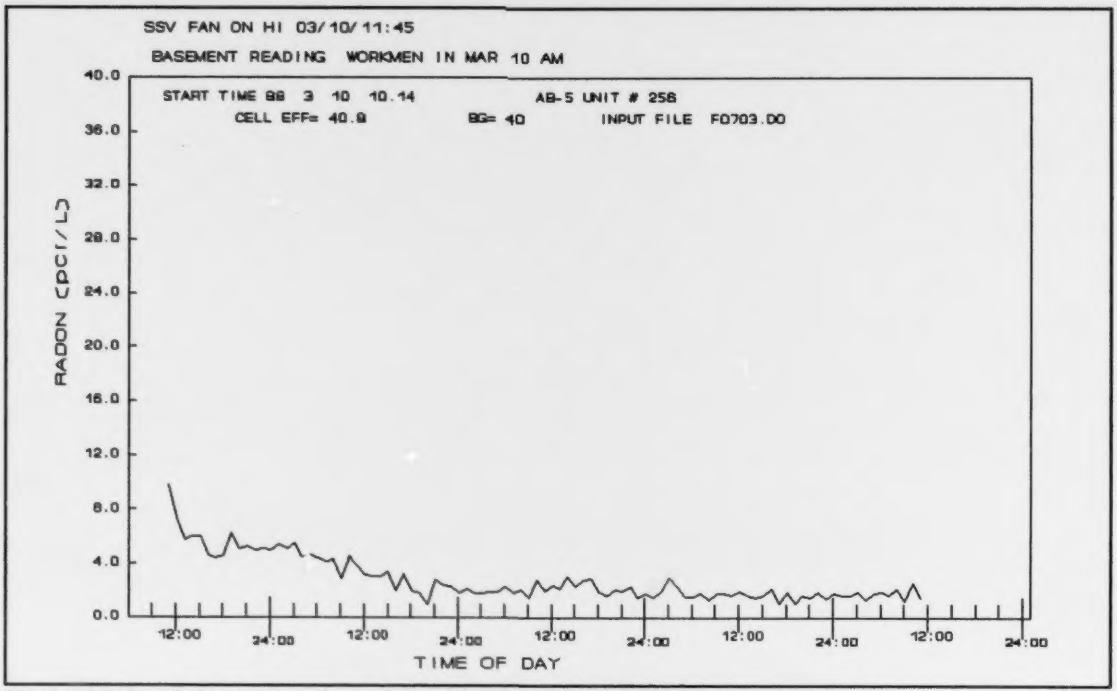


Figure 07-3. Sub-slab suction with mitigation fan at DPmax

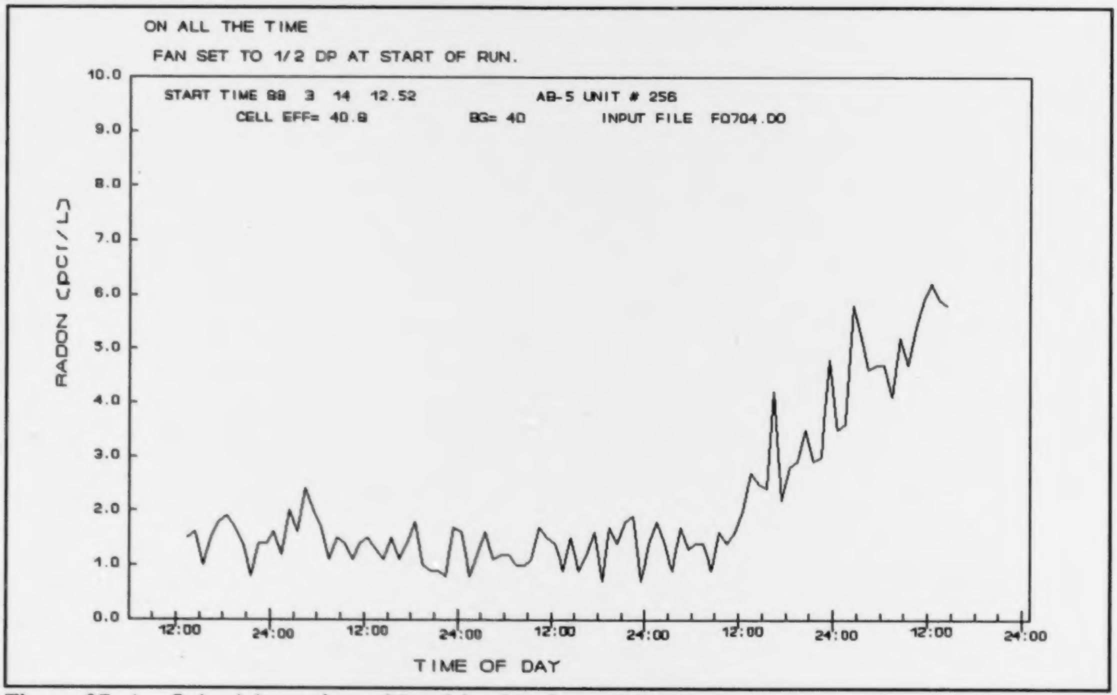


Figure 07-4. Sub-slab suction with mitigation fan at 0.5 DPmax

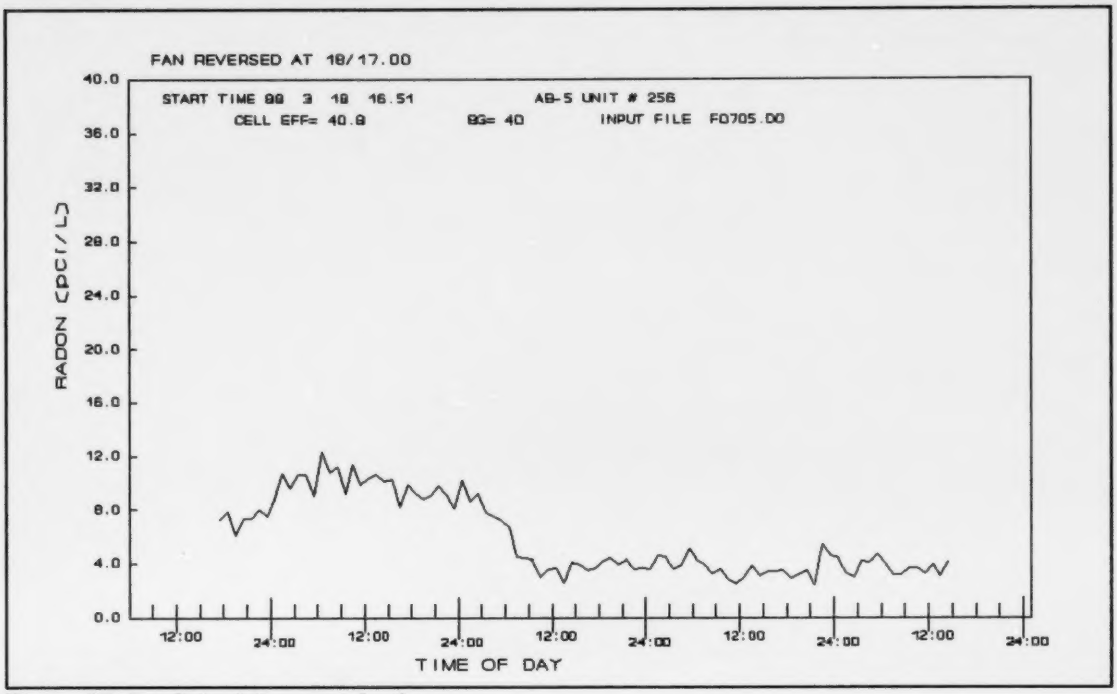


Figure 07-5. Sub-slab pressurization

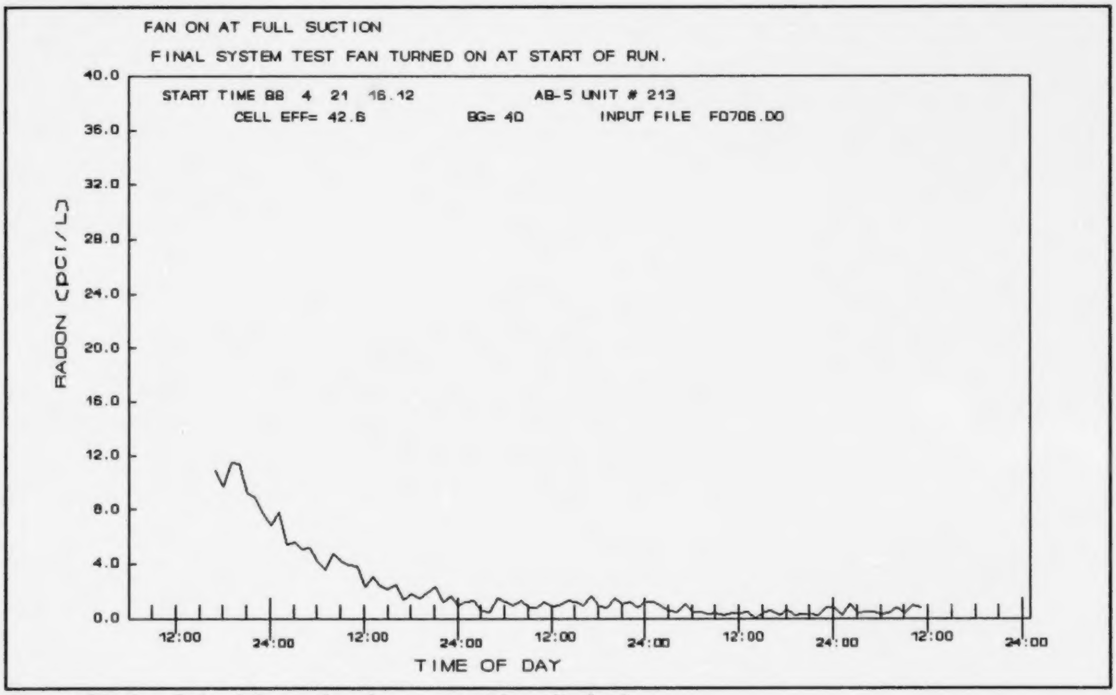
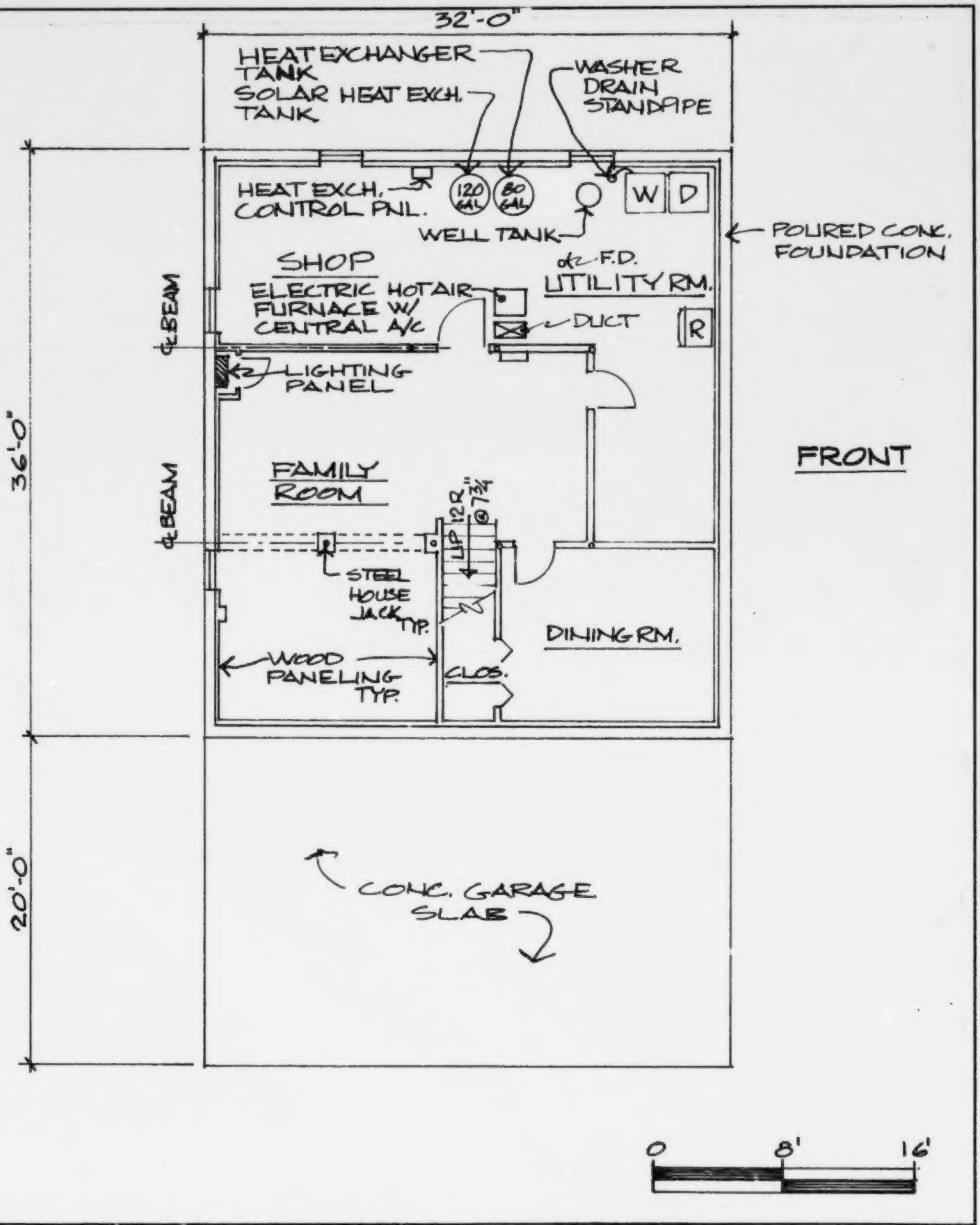
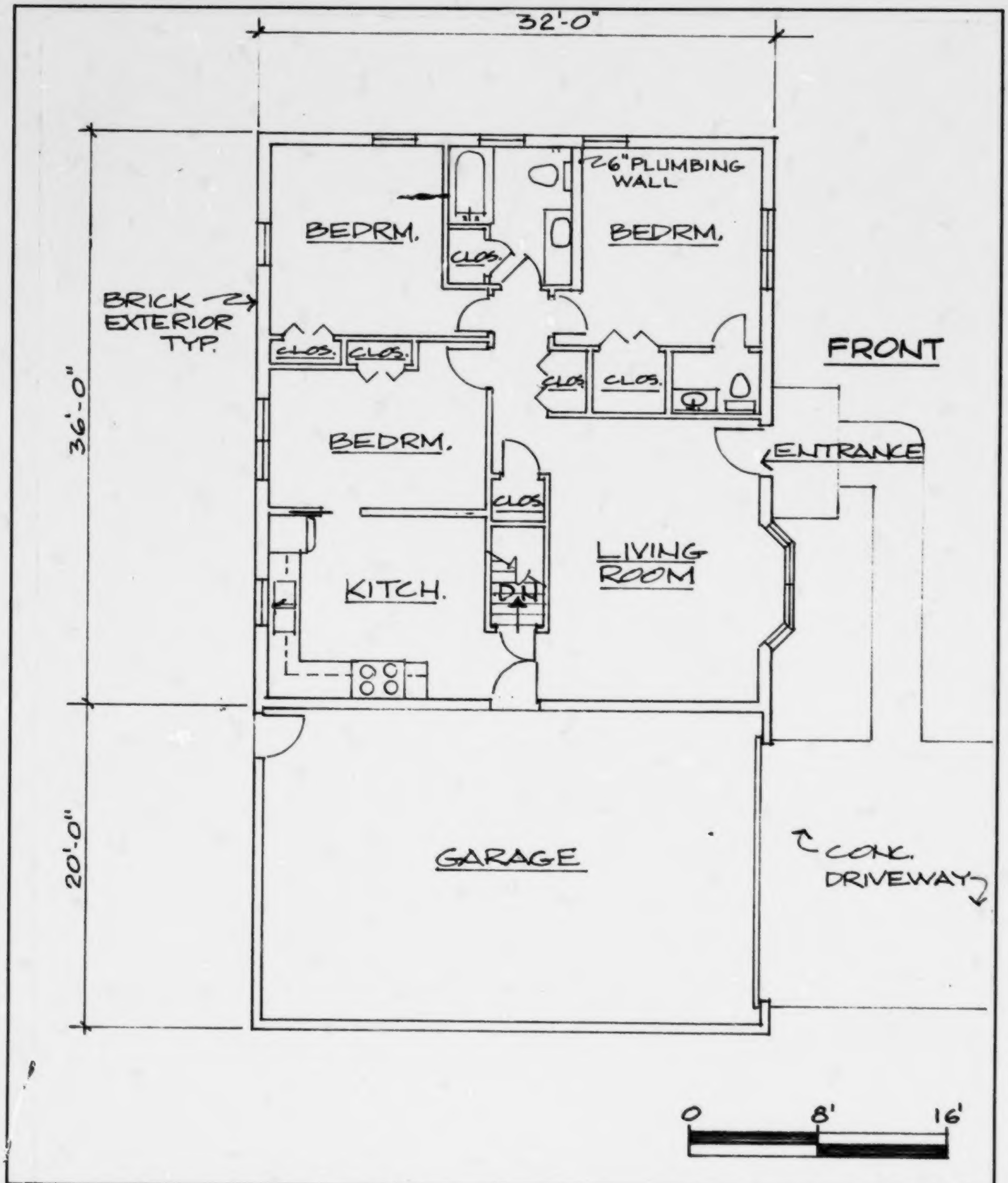


Figure 07-6. Sub-slab suction (permanent installation)



ACRES Acres International Corporation	**LOW COST REDUCTION OF INDOOR RADON**		**HOUSE NUMBER**
	BASEMENT/FOUNDATION PLAN	**Date:** 2/26/88	7
	House Group: FULL BASEMENT	**PHASE:**	



Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON

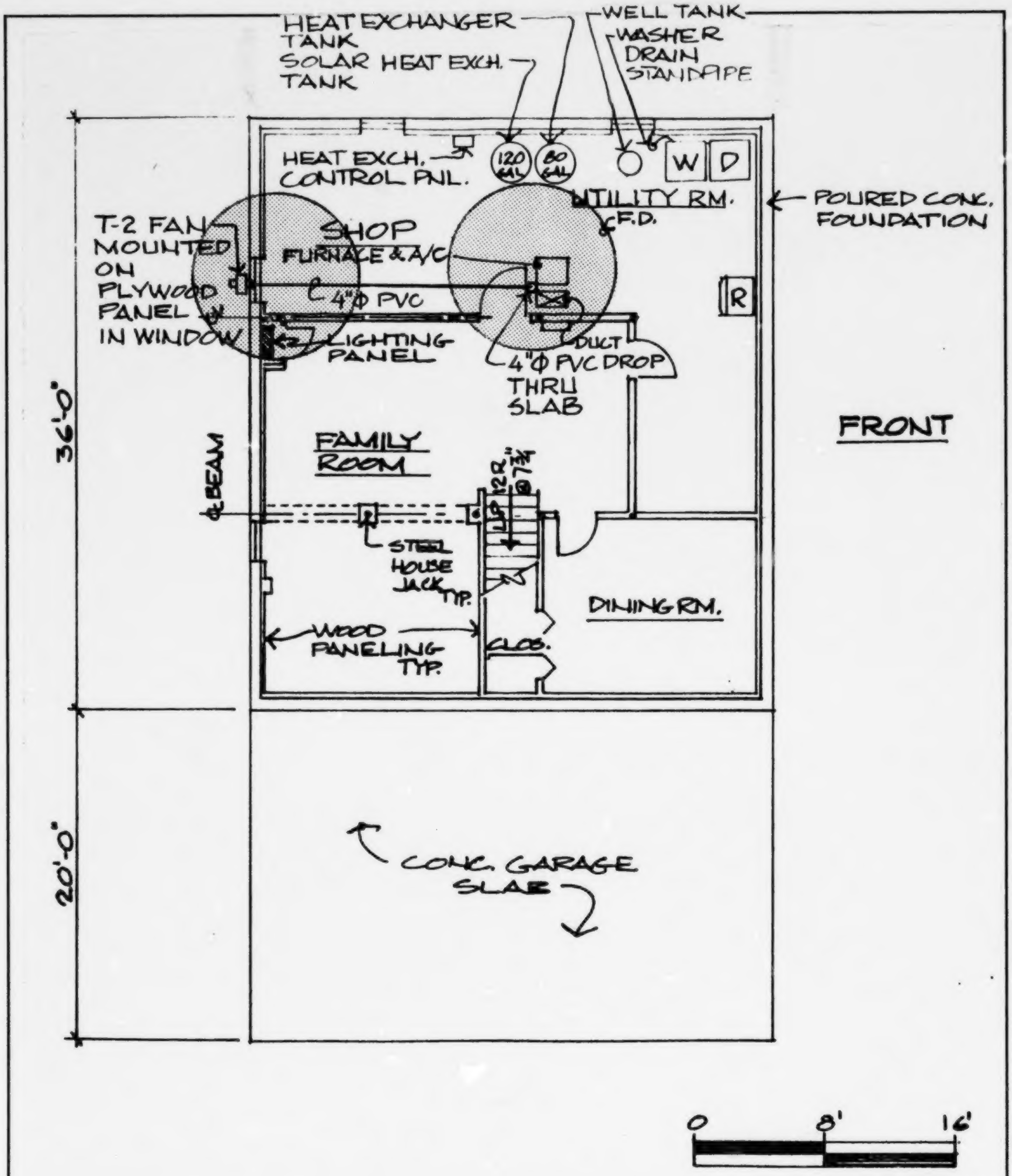
HOUSE NUMBER 7

GRADE LEVEL PLAN

Date: 2/26/88

House Group: **FULL BASEMENT**

PHASE:



ACRES
Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON

BASEMENT/FOUNDATION PLAN

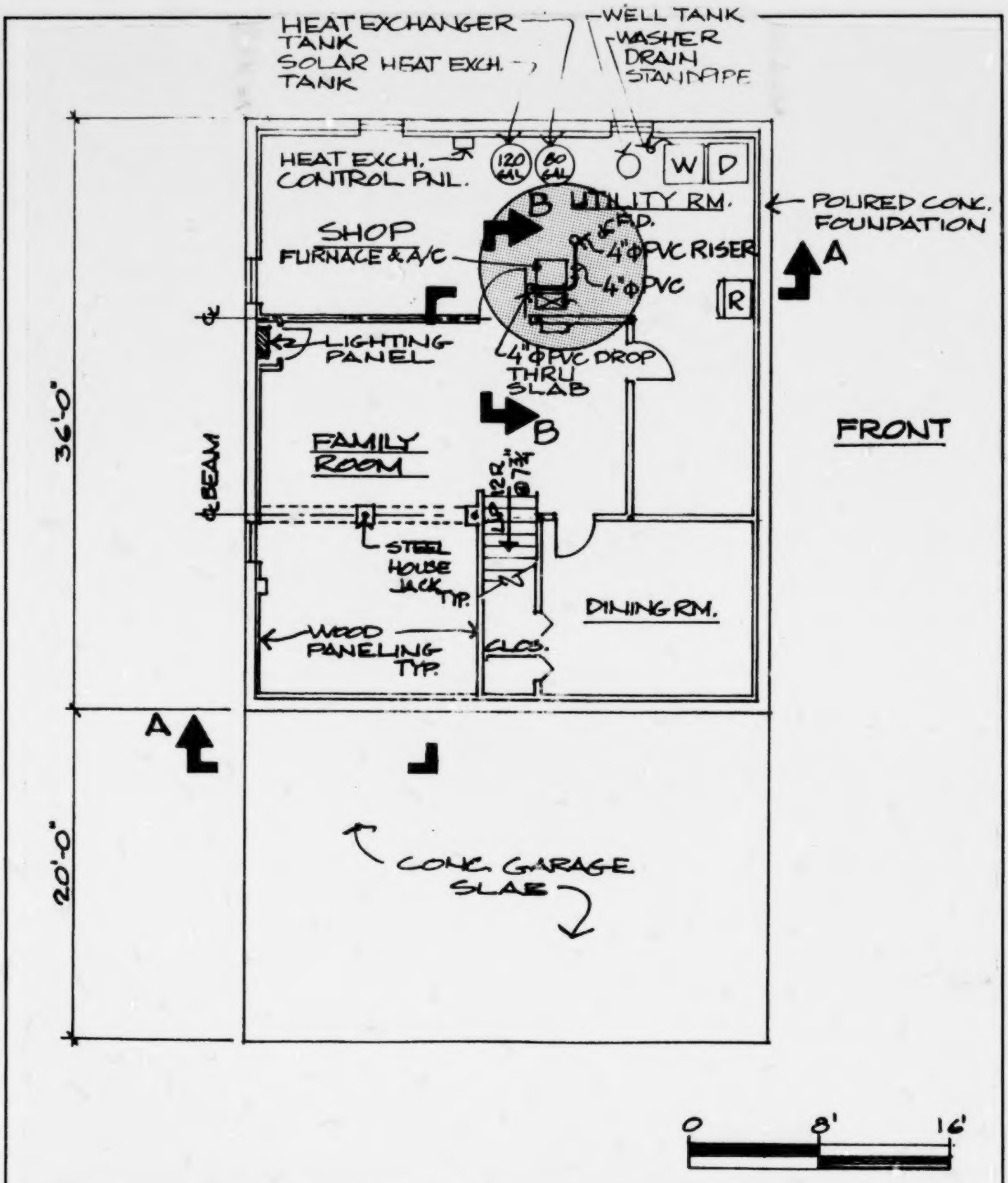
Mitigation system: SUB-SLAB SUCTION

Date: MAY 1988

PHASE: TEST

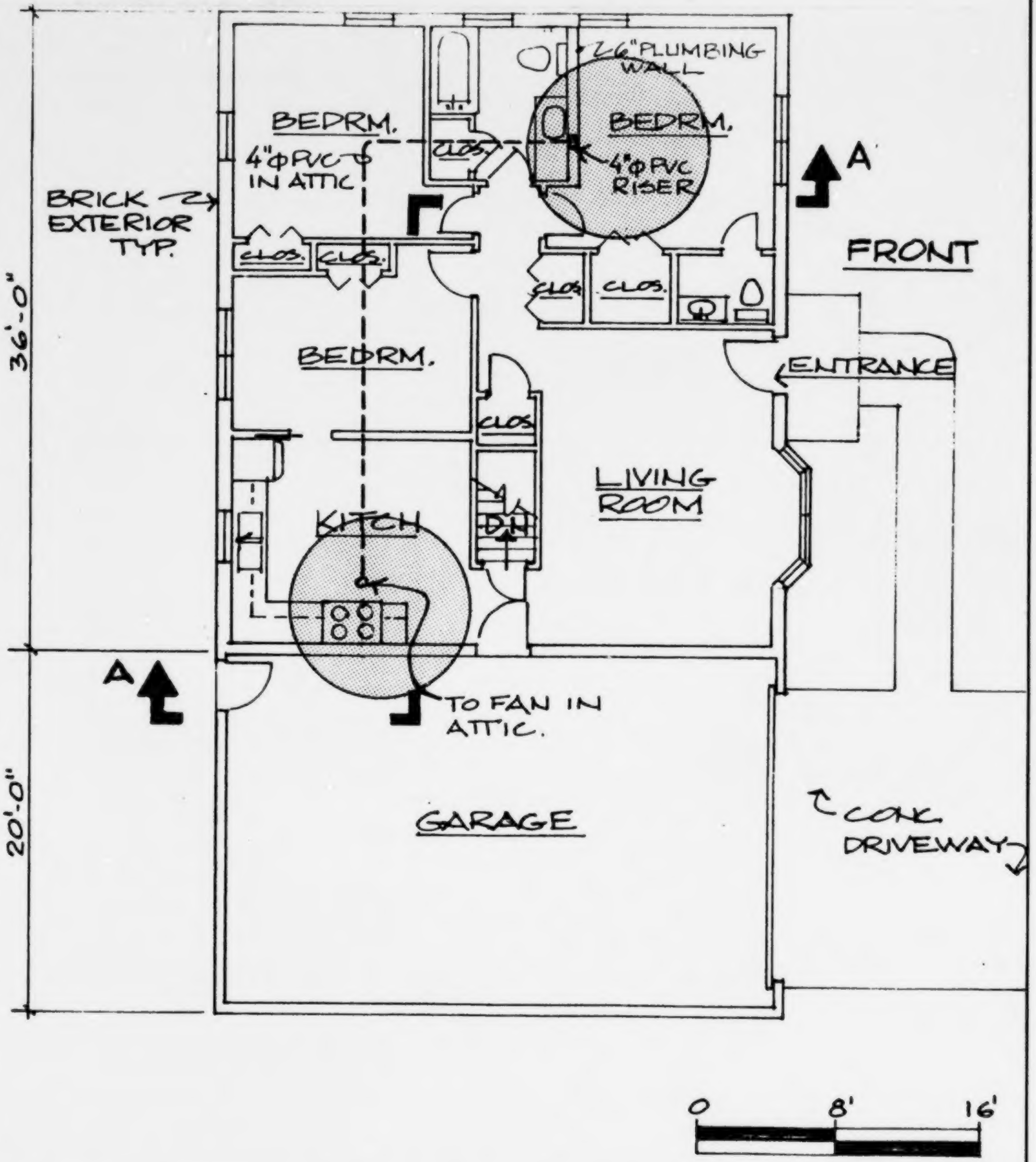
HOUSE NUMBER

7



ACRES
Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
BASEMENT/FOUNDATION PLAN	Date: MAY 1988	7
Mitigation system: SUB-SLAB SUCTION	PHASE: Final	



ACRES
Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON

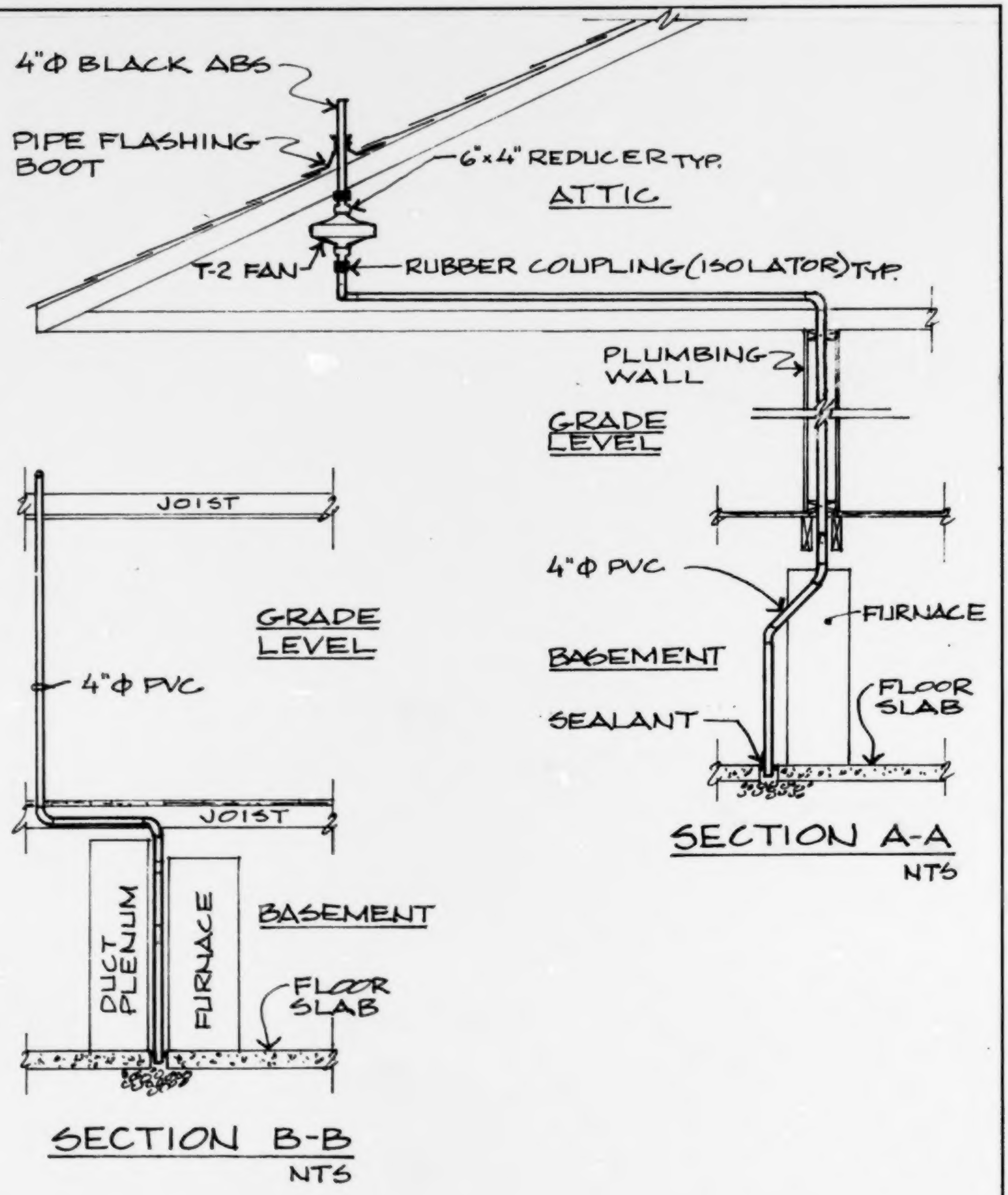
GRADE LEVEL PLAN

Mitigation system: SUB-SLAB SUCTION

Date: MAY 1988

PHASE: FINAL

HOUSE NUMBER 7



ACRES
Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON

SECTIONS/DETAILS

Date: MAY 1988

HOUSE NUMBER
7

Mitigation system: SUB-SLAB SUCTION

PHASE: FINAL

HOUSE 11

1 GENERAL DESCRIPTION

This large (170 m^2) split-level house with an attached garage was built in the early 1980's on a country site at the top of a hill to the south of Bellbrook. The foundation walls are of poured concrete, with a embossed brick pattern. The exterior walls are of brick and stained wood siding. One half of the basement section is partly finished with a ceiling and central paneled frame wall, but the section on the other side of the wall (rear of the house) is unfinished and used as a workshop and storage area. The concrete floor is bare in the workshop, and is covered with loose carpet in the other half. Heating is by an upflow forced-air gas furnace with air conditioning located in the storage room and heat distribution ducts for the upper level running the length of the house. The adjacent slab has sub-slab air distribution ducts, supplied by a single large metal duct that passes through the stub wall by the furnace. The water softener and the air conditioning condensate discharge to a trapped floor drain.

2 INVESTIGATION

A sub-floor permeability and connectivity test was carried out in this house as part of the EPA pre-selection process in January 1988. The close/distant pressure ratio (sub-slab depressurization 0.3 m from suction hole/depressurization 6 m from hole) was 61 Pa/18 Pa = 3.4, with a suction of 610 Pa in the vacuum cleaner nozzle, indicating both good communication and a low fill impedance. The fill visible through the 30 mm hole appeared to be pea gravel. Sub-slab radon concentrations were 1,100 pCi/L. A short-term radon survey found that concentrations in the slab-on-grade family room ranged from 9 to 25 pCi/L, and averaged 16.6 pCi/L over a 94 hour period.

3 MITIGATION

As a result of the good results from the sub-slab communication test, the mitigation system chosen for demonstration was sub-slab exhaust in the basement portion alone. The slab-on-grade section would not be treated unless the basement treatment was ineffective. The system was planned in two stages: a temporary system to check the effectiveness of the system, followed by a permanent installation.

A temporary system was installed in early March 1988 in the work room section of the basement with a single exhaust point located close to the stub wall. This was expected to treat the basement floor, and also reduce the soil gas flow into the upper level. There was about 150 mm of gravel beneath the floor at this point. The T-2 exhaust fan was temporarily mounted on a plywood board cut to fit a basement window located at the far end of the basement.

The fan drew sub-slab air at a rate of 12 L/s and 170 pCi/L radon concentration at the low suction of 250 Pa, and 15 L/s at maximum suction of 350 Pa. Similar results were obtained for house radon with the fan operating at either setting. In the basement workshop radon levels ranged from 3 to 7 pCi/L, averaging 4.0 pCi/L (Figures 11-2 and 11-4), while in the upstairs slab-on-grade family room levels ranged from 2 to 4 pCi/L, averaging 2.4 pCi/L (Figure 11-3). These can be contrasted with the range of 19 to 32 pCi/L and average of 24.4 pCi/L then measured in the workshop with the fan off (Figure 11-4).

The fan was then reversed to pressurize the sub-slab space. This might produce a fresh-air "bubble" of sufficient dimension and force to restrict entry of radon. With the fan providing a pressure of 250 Pa and a flow of 11 L/s, radon levels in the workshop ranged from 6 to 14 pCi/L and averaged 9.1 pCi/L over a 52 hour period. Although this represented a considerable improvement over original concentrations, it was clearly not as effective as sub-slab exhaust. this was confirmed when, with the fan returned to suction, radon concentrations ranged from 2 to 4 pCi/L and averaged 2.9 pCi/L at a suction of 150 Pa and a flow of 13 L/s.

The fan controller was reset to maximum to investigate the distribution of sub-slab suction. With the fan establishing a flow of 14 L/s and a suction of 330 Pa at the system riser, suctions were measured at the test holes which had been drilled through the for the pre-selection diagnostic testing. These holes were: hole 1, 0.3 m from pre-selection suction hole and 1 m from the sub-slab suction pipe; hole 2, 5 m from the suction pipe; hole 3, 6 m from the pre-selection suction point and 7 m from the sub-slab pipe; and hole 4, 4.5 m from the sub-slab pipe in the opposite direction from holes 2 and 3. The sub-slab depressurizations at these holes were: 32 Pa at hole 1, 5 Pa at hole 3, 12 Pa at hole 4, and 2 Pa at new hole 5, which was drilled through the slab in the far corner of the basement rec room, approximately 10 m from the riser. These pressures were somewhat lower than expected from the pre-selection tests; the near/far ratio with the sub-slab system in place was 32 Pa/5 Pa = 6.4 (hole 1/hole 3), compared to the ratio of 3.4 for these same test holes observed during the pre-selection diagnostics.

A second exhaust point was added at the opposite end of the workroom to provide a more uniform pressure distribution under the basement floor slab. A sample of the sub-slab material was taken through the hole cut in the floor slab for the exhaust pipe. The material was comprised almost entirely of pebbles ranging in size from 5 to 20 mm diameter, with only a small amount of finer material. The site material exposed at the bottom of the hole was comprised of small stones in the 2 to 5 mm range together with an equal amount of sandy clay in 1 mm lumps.

With the fan set at approximately half of maximum suction, identical pressure drops of 150 Pa were established at both riser pipes, while flow rates of 9 and 13 L/s were measured at riser 1 (original position) and riser 2 respectively. At that time, suctions of 29, 32, 12 and 16 Pa were measured at holes 1, 2, 4 and 5, and pressure differences across the building shell due to winds were observed to vary from -5 to +7 Pa. Radon concentrations in the workshop ranged from 2 to 8 pCi/L, averaging 3.7 pCi/L.

The fan was then set to maximum speed, suctions in risers 1 and 2 were identical at 250 Pa, and flows were 13 and 21 L/s respectively. The corresponding pressure differences induced at holes 1, 2, 4 and 5 were measured as 54, 64, 34, and 27 Pa. The radon concentrations in the workroom ranged from 2 to 6 pCi/L, averaging 3.8 pCi/L.

The increased suction and increased sub-slab pressure uniformity did not change the average radon concentration significantly, indicating that the remaining routes of radon entry were not in the basement portion of the house.

4 FINAL INSTALLATION

During the first week of April 1988, the temporary sub-slab ventilation system was replaced by a permanent system exiting through a hole cut in the rear basement wall. A plastic-bodied in-line T-2 fan was mounted externally and connected to the interior piping by a 6-to-4-in. adaptor followed by a 4 inch rubber connector to the piping.

To test that radon concentrations were reduced in all parts of the house, measurements were made simultaneously in the workroom, rec room, and slab-on-grade family room. With the fan off for one day, basement radon concentrations ranged from 1 to 21 pCi/L, averaging 8.2 and 10.3 pCi/L in the rec room and workshop respectively (Figures 11-10 and 11-9). Upstairs levels on the slab-on-grade family room with the fan off ranged from 1 to 14 pCi/L, averaging 5.1 pCi/L

(Figure 11-11). With the fan running at maximum suction, radon concentrations at all three sites ranged between 1 and 2 pCi/L and averaged 1.2 pCi/L (Figures 11-9, -10 and -11).

5 OTHER MEASUREMENTS

The 1987 charcoal canister survey gave a reading of 28.8 pCi/L in the basement work room, and the owners had made a second measurement of 33.3 pCi/L. The short-term, pre-selection radon monitor survey in January 1988 found radon concentrations in the family room on the slab-on-grade ranged from 9 to 25 pCi/L, averaging 16.6 pCi/L.

A pre-mitigation alpha-track measurement over the period December 1987 to February 1988 gave average radon concentrations of 17.3 pCi/L in the kitchen and 28.9 pCi/L in the basement.

A post-mitigation alpha-track measurement over the period May to August 1988 gave an average radon concentrations of 0.7 pCi/L in the living area above the basement, 1.1 pCi/L in the slab-on-grade family room, and 2.3 pCi/L in the basement.

The radiation field in the basement ranged from 5 to 6 μR/h over the entire floor slab. The field over the site outside the house ranged from 5 to 8 μR/h, averaging 6 μR/h.

MEASUREMENTS SUMMARY FOR HOUSE 11

PYLON AB-5 HOURLY MONITORING

MITIGATION SYSTEM	TEST DATE	TEST STATUS	RADON(pCi/L) RANGE	RADON(pCi/L) MEAN	ROOM*/ DURATION	FIG.
pre-selection	01/88		9-25	16.6	family; 94 hrs	11-1
sub-slab suction (one pipe)	03/88	DPmax	2- 4	2.7	family; 68 hrs	11-3
		DPlow	2- 3	2.4	family; 21 hrs	11-3
		DPmax	3- 6	4.0	workshop; 55 hrs	11-2
		DPlow	3- 5	4.0	workshop; 38 hrs	11-2
		DPlow	3- 7	4.2	workshop; 46 hrs	11-4
		fan off	19-32	24.4	workshop; 38 hrs	11-4
sub-slab pressure (one pipe)	03/88	DPlow	6-14	9.1	workshop; 68 hrs	11-5
sub-slab suction (one pipe)	03/88	0.5DPmax	2- 4	2.9	workshop; 90 hrs	11-6
2-point sub-slab suction	03/88	0.5DPMax	2- 8	3.7	workshop; 98 hrs	11-7
		DPmax	2- 6	3.8	workshop; 98 hrs	11-8
2-point sub-slab suction (permanent)	04/88	fan off	1-14	5.1	family; 23 hrs	11-11
		DPmax	1- 2	1.1	family; 41 hrs	11-11
		fan off	2-21	10.3	workshop; 23 hrs	11-9
		DPmax	1- 2	1.3	workshop; 37 hrs	11-9
		fan off	1-21	8.2	rec room; 23 hrs	11-10
		DPmax	1- 2	1.1	rec room; 41 hrs	11-10

* The workshop and rec room are in the basement; the family room is on the adjoining slab-on-grade.

Average pre-mitigation Pylon results (presented in Tables VIII and 3):

Basement

Average of pre-mitigation portion of Figure 11-4 (38 hours total) = 24.4 pCi/L (March).
Average of pre-mitigation portion of Figure 11-9 and 11-10 (46 hrs total) = 9.2 pCi/L (April).

Slab on grade

Average of Figure 11-1 (94 hours total) = 16.6 pCi/L (January)
Average of pre-mitigation portion of Figure 11-11 (23 hrs total) = 5.1 pCi/L (April)

Average post-mitigation Pylon results (presented in Table VIII):

Basement

One suction point — Fig. 11-6 (fan at 0.5 DPmax) and reduced-fan portions of Figs. 11-2 and 11-4 (174 hours total) = 3.5 pCi/L.
Two suction points — Fan-on portions of Figs. 11-9 and 11-10 (78 hrs total) = 1.2 pCi/L.

Slab on grade

Two suction points — Fig. 11-11 (fan at DPmax) (41 hrs total) = 1.1 pCi/L (April).

SYSTEMS MEASUREMENTS

PHASE	MITIGATION SYSTEM	TEST DATE	MEASUREMENTS			COMMENT
			SUCTION (Pa)	FLOW (L/s)	RADON (pCi/L)	
1	pre-selection	01/88	610		1100	suction at slab
			61			at hole 1
			32			at hole 2
			18		1100	at hole 3
			29			at hole 4
					28	basement air
					38	floor drain
					75	wall/floor joint
1	sub-slab suction (one point)	03/88	320	15		at riser; DPmax
			250	12	170	at riser; DPlow
					2	workshop air
					4	at riser; fan off
1	sub-slab pressure	03/88	-250*	11		at riser; DPlow
1	sub-slab suction (one point)	03/88	330	14		at riser; DPmax
			32			at hole 1
			5			at hole 3
			12			at hole 4
			2			at hole 5
			150	13		at riser; 0.5DPmax
1	2-point sub-slab suction	03/88	150	9		riser 1; 0.5DPmax
			150	13		riser 2; 0.5DPmax
			29			at hole 1
			32			at hole 2
			12			at hole 4
			16			at hole 5
			5 to -7*			across shell/winds
			250	13		riser 1; DPmax
			250	21		riser 2: DPmax
			54			at hole 1
			64			at hole 2
			34			at hole 4
			27			at hole 5

* "Negative suction" denotes pressurization relative to house.

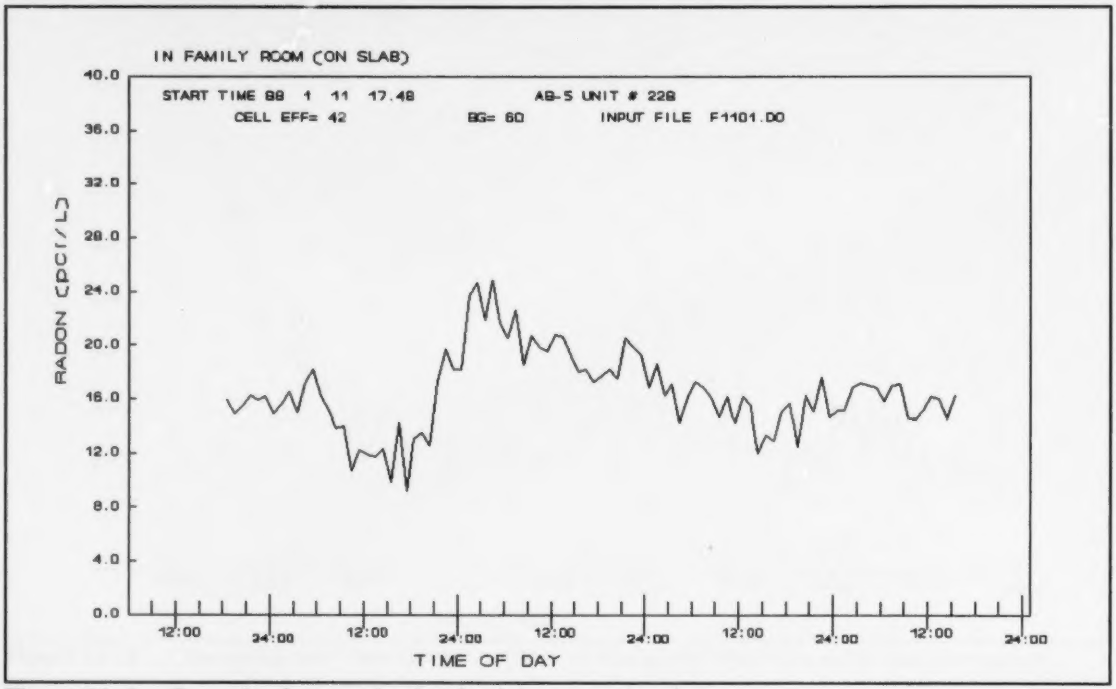


Figure 11-1. Pre-selection monitoring in slab-on-grade wing

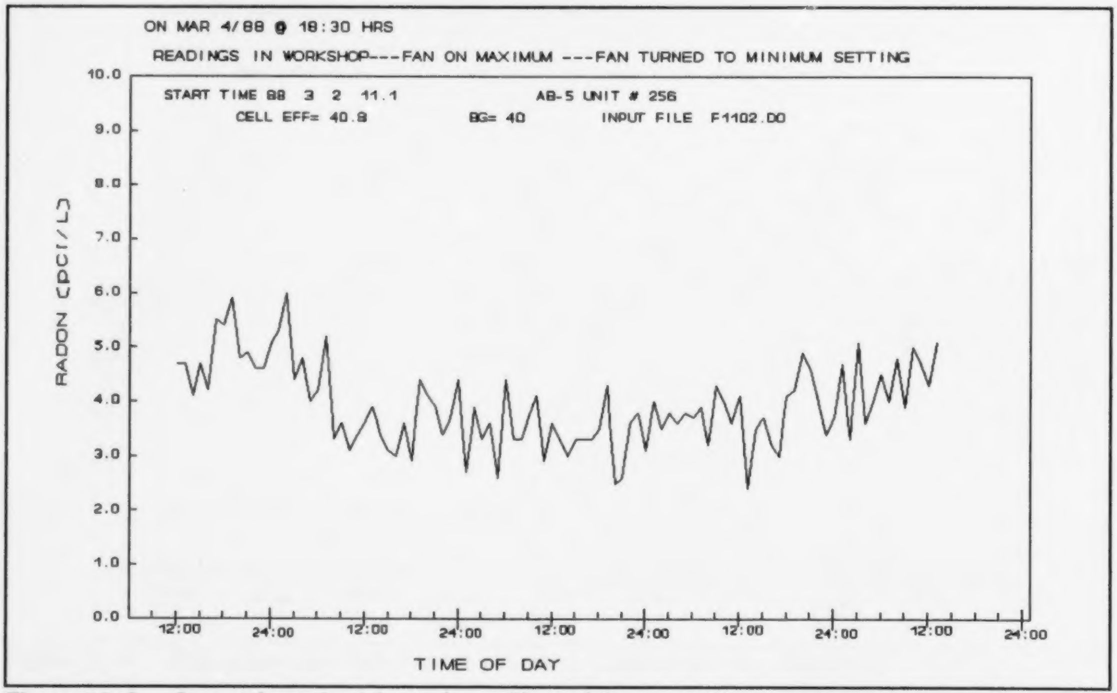


Figure 11-2. One-point sub-slab suction, effect of fan speed (basement measurements)

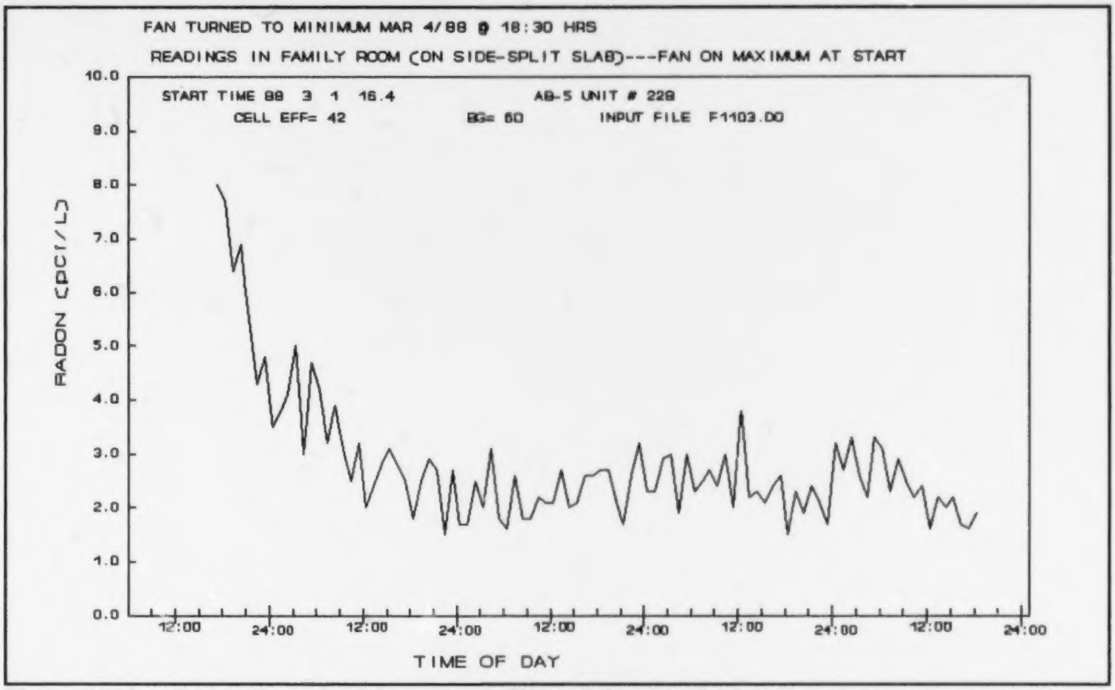


Figure 11-3. One-point sub-slab suction, effect of fan speed (slab-on-grade measurements)

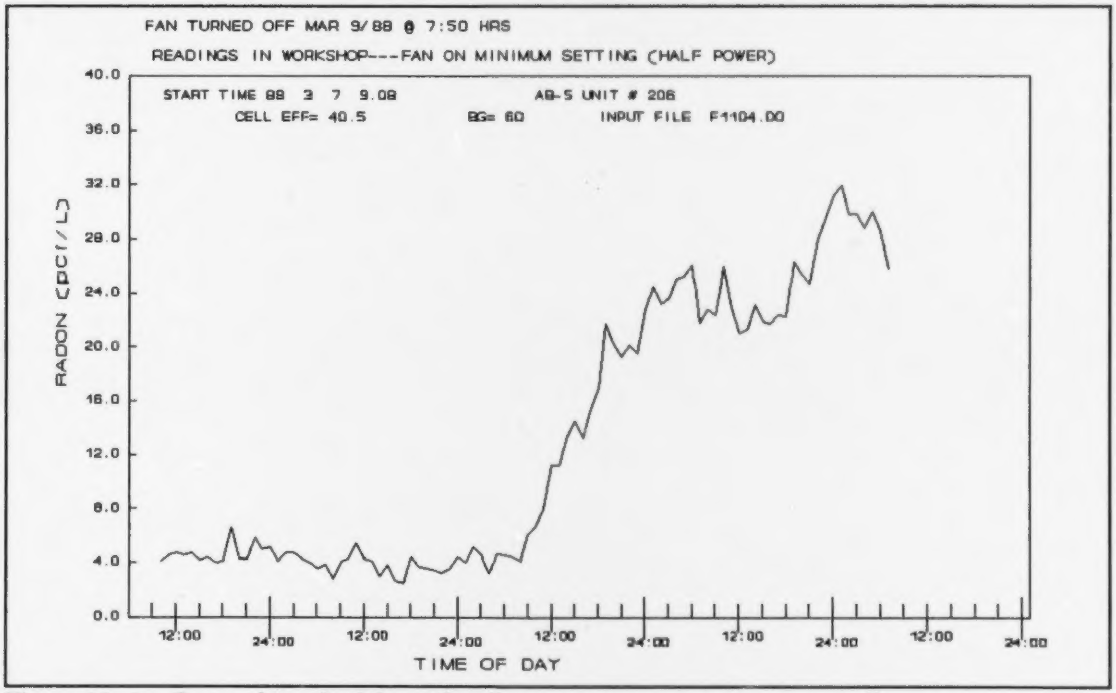


Figure 11-4. One-point sub-slab suction (basement measurements, repeated)

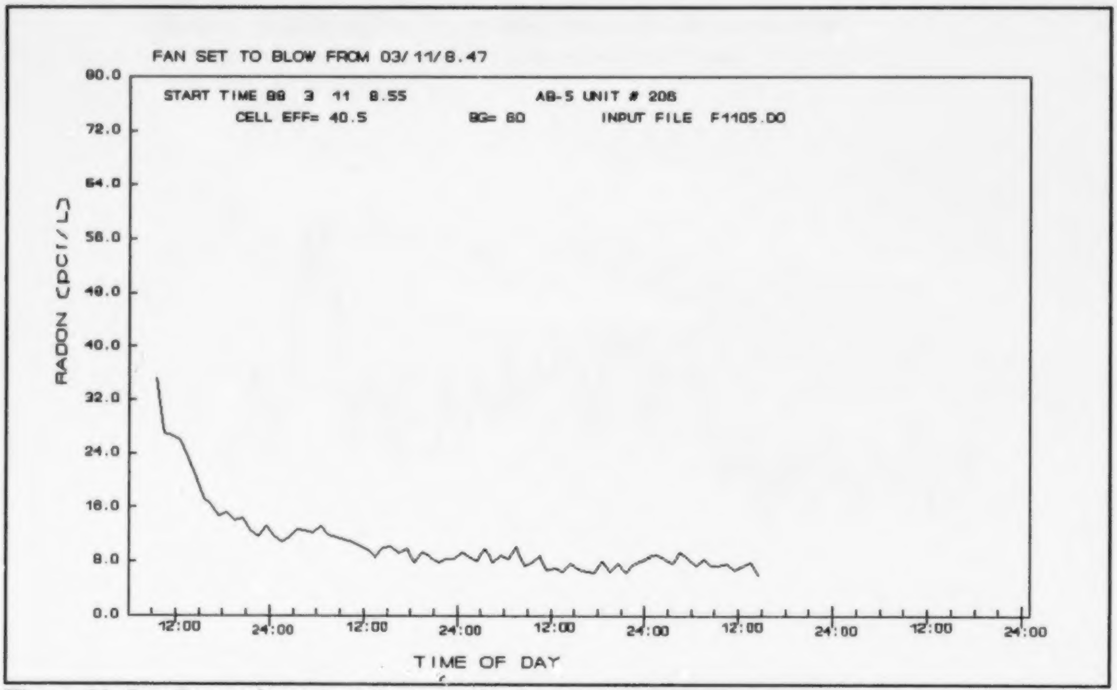


Figure 11-5. One-point sub-slab pressurization (basement measurements)

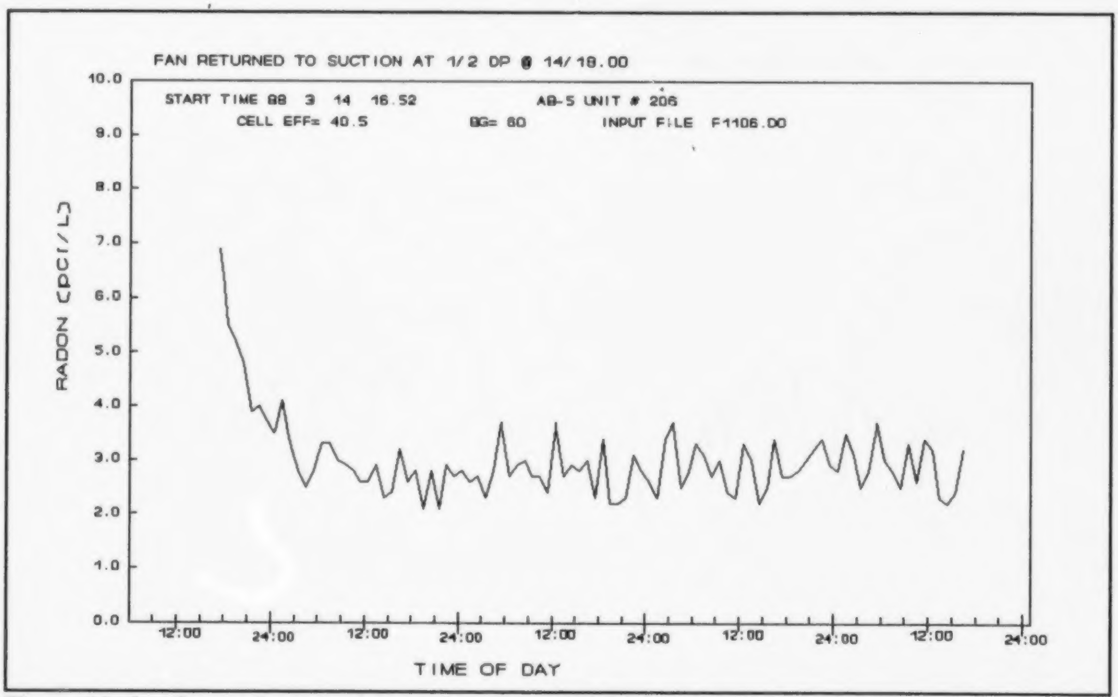


Figure 11-6. One-point sub-slab suction, fan at 0.5 DPmax (basement measurements)

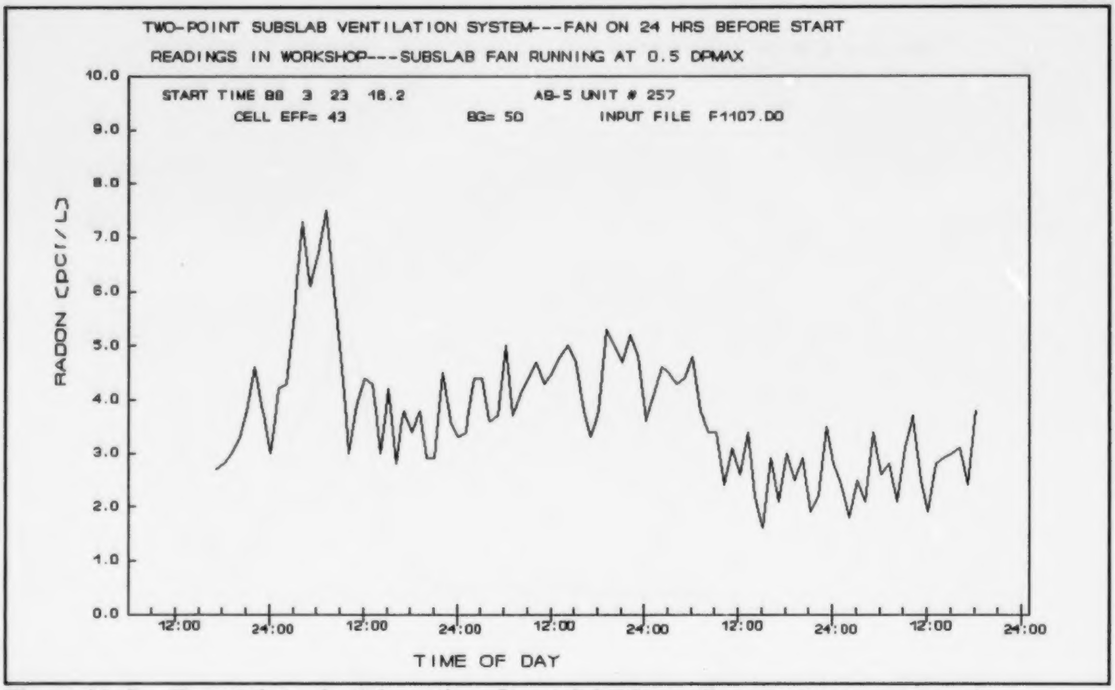


Figure 11-7. Two-point sub-slab suction, fan at 0.5 DPmax (basement measurements)

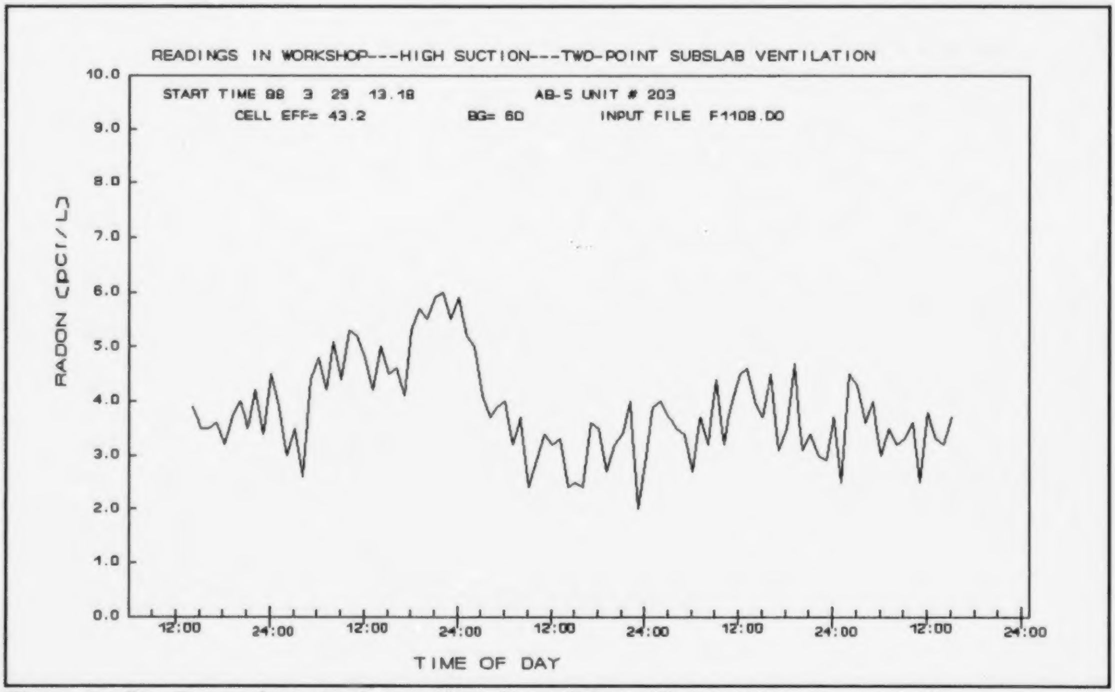


Figure 11-8. Two-point sub-slab suction, fan at DPmax (basement measurements)

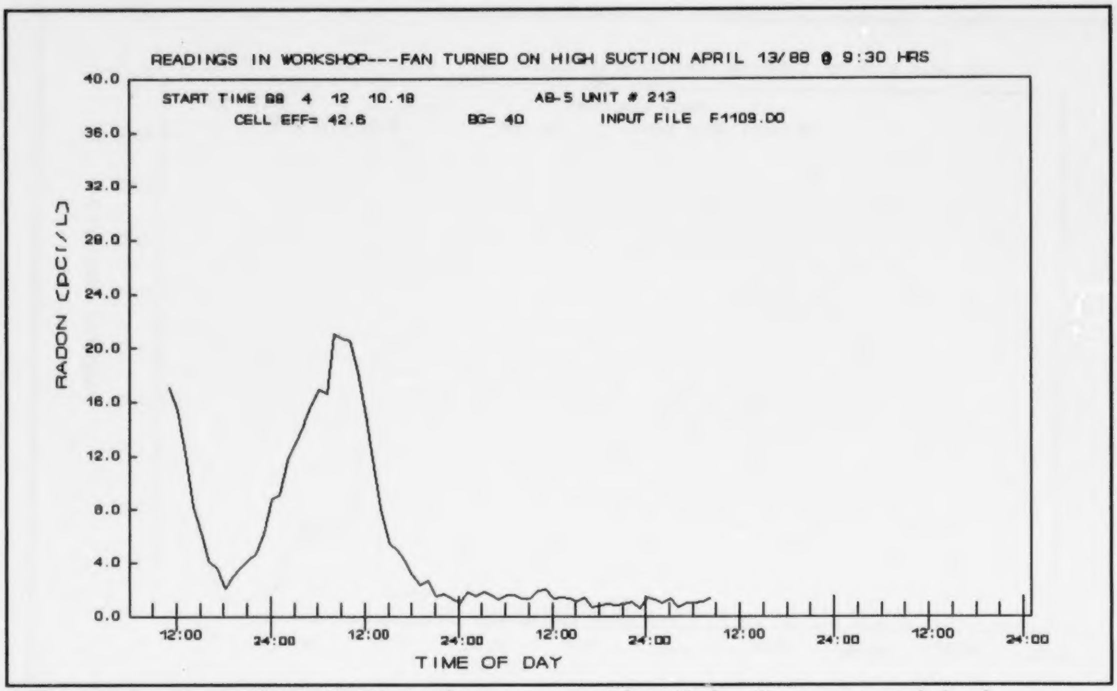


Figure 11-9. Two-point sub-slab suction, permanent installation (basement workshop)

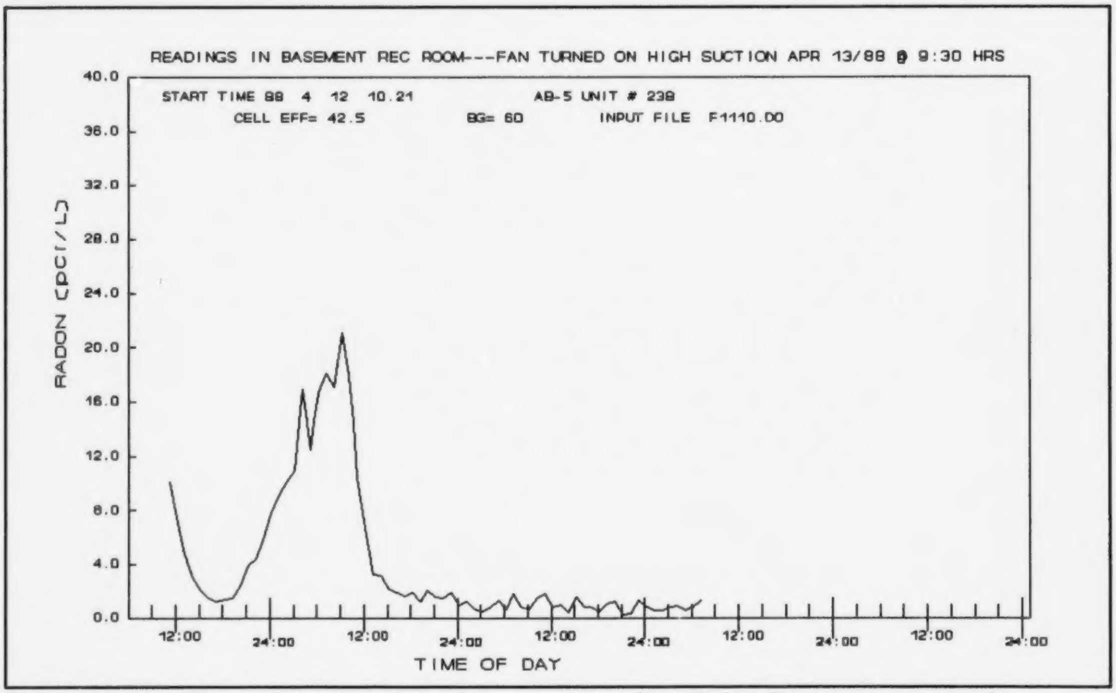


Figure 11-10. Two-point sub-slab suction, permanent installation (basement rec room)

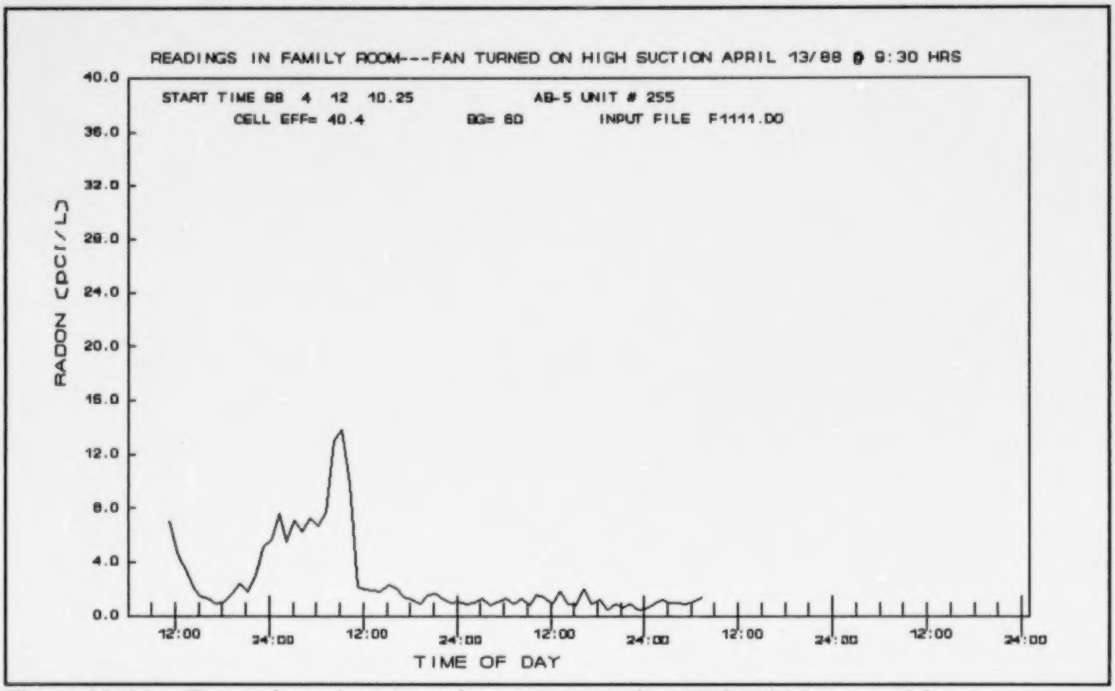
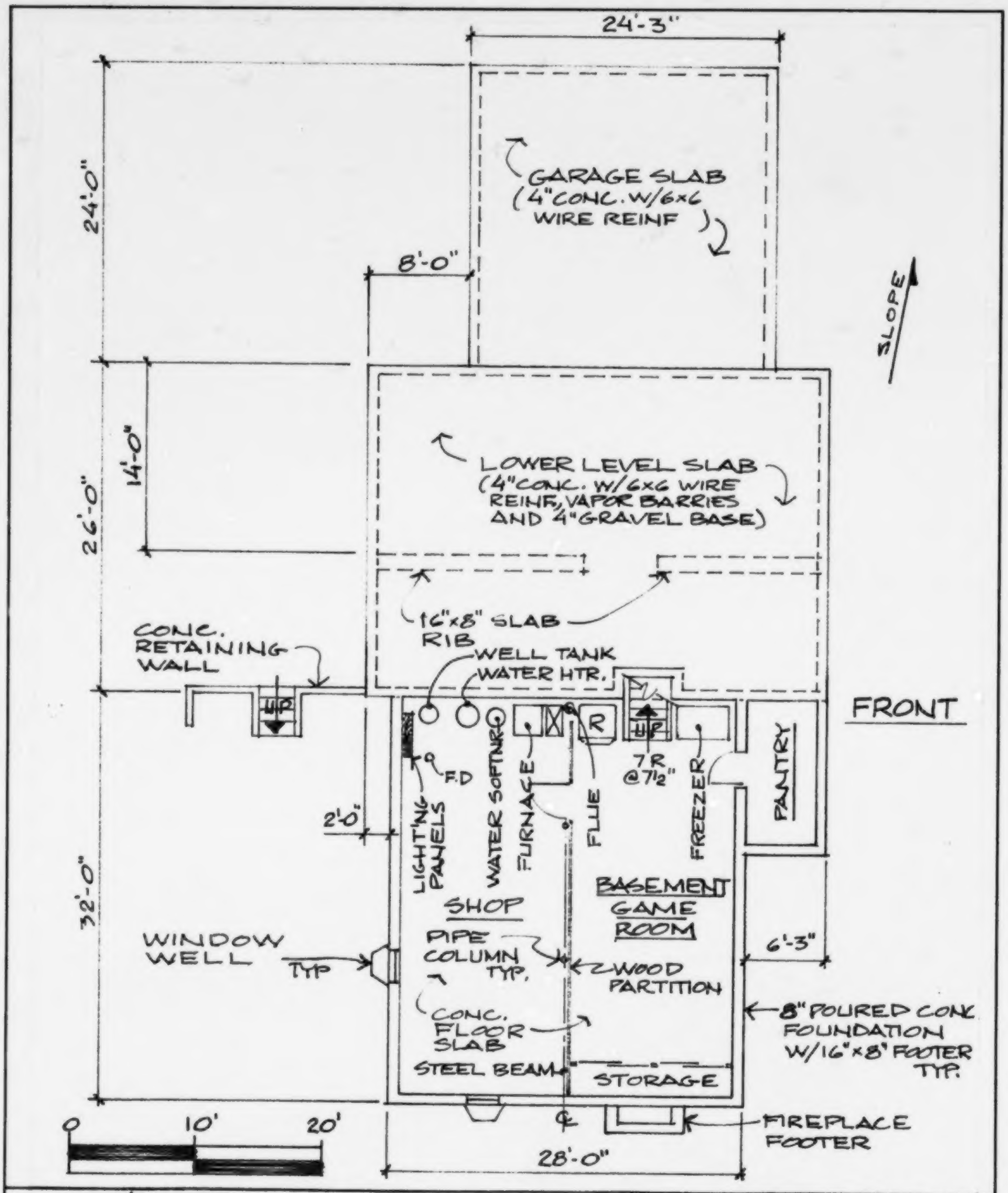


Figure 11-11. Two-point sub-slab suction, permanent installation (slab on grade)



ACRES
Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON

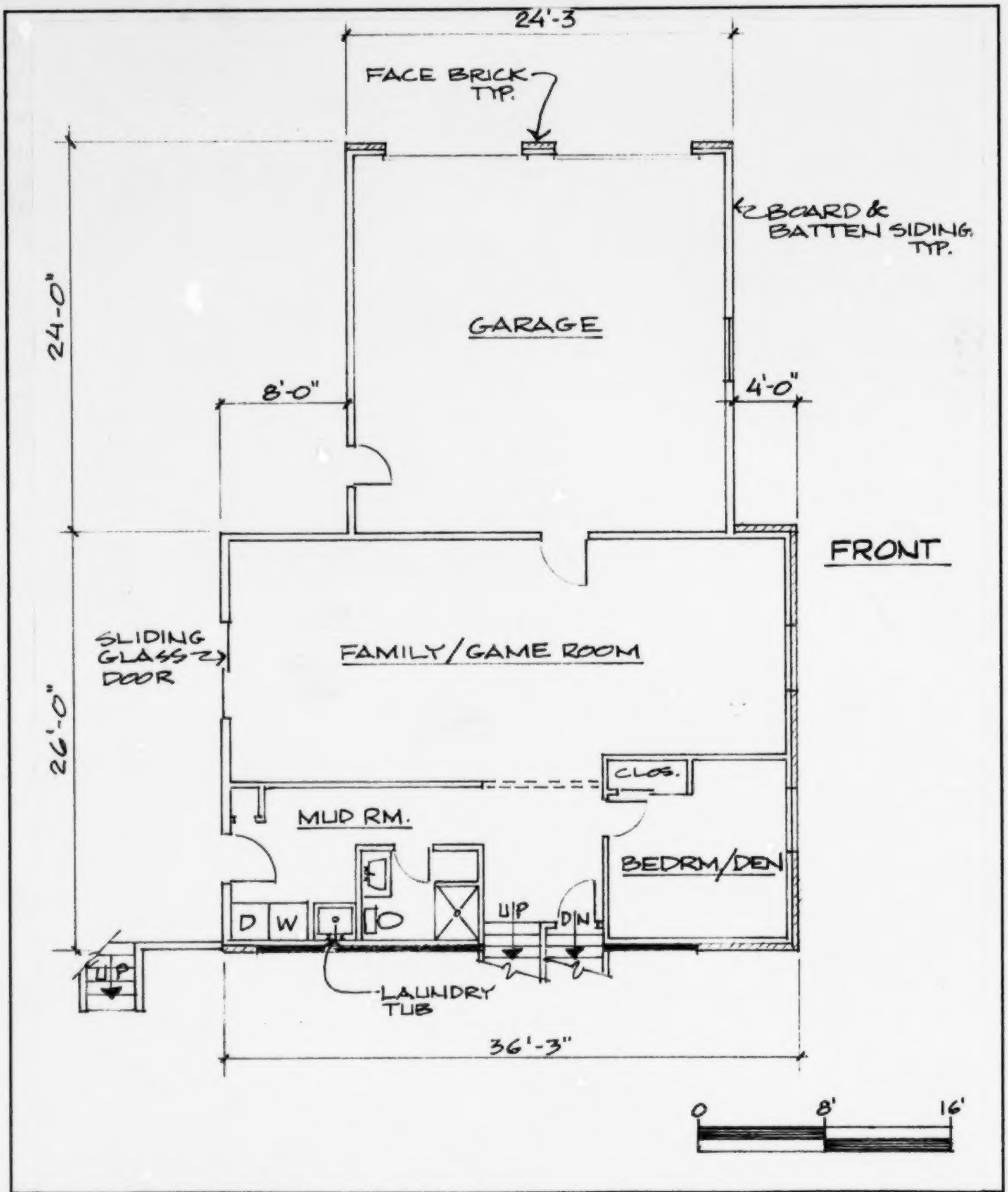
HOUSE NUMBER: 11

BASEMENT/FOUNDATION PLAN

Date: 2/26/88

House Group: **PARTIAL BASEMENT**

PHASE:



ACRES
Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON

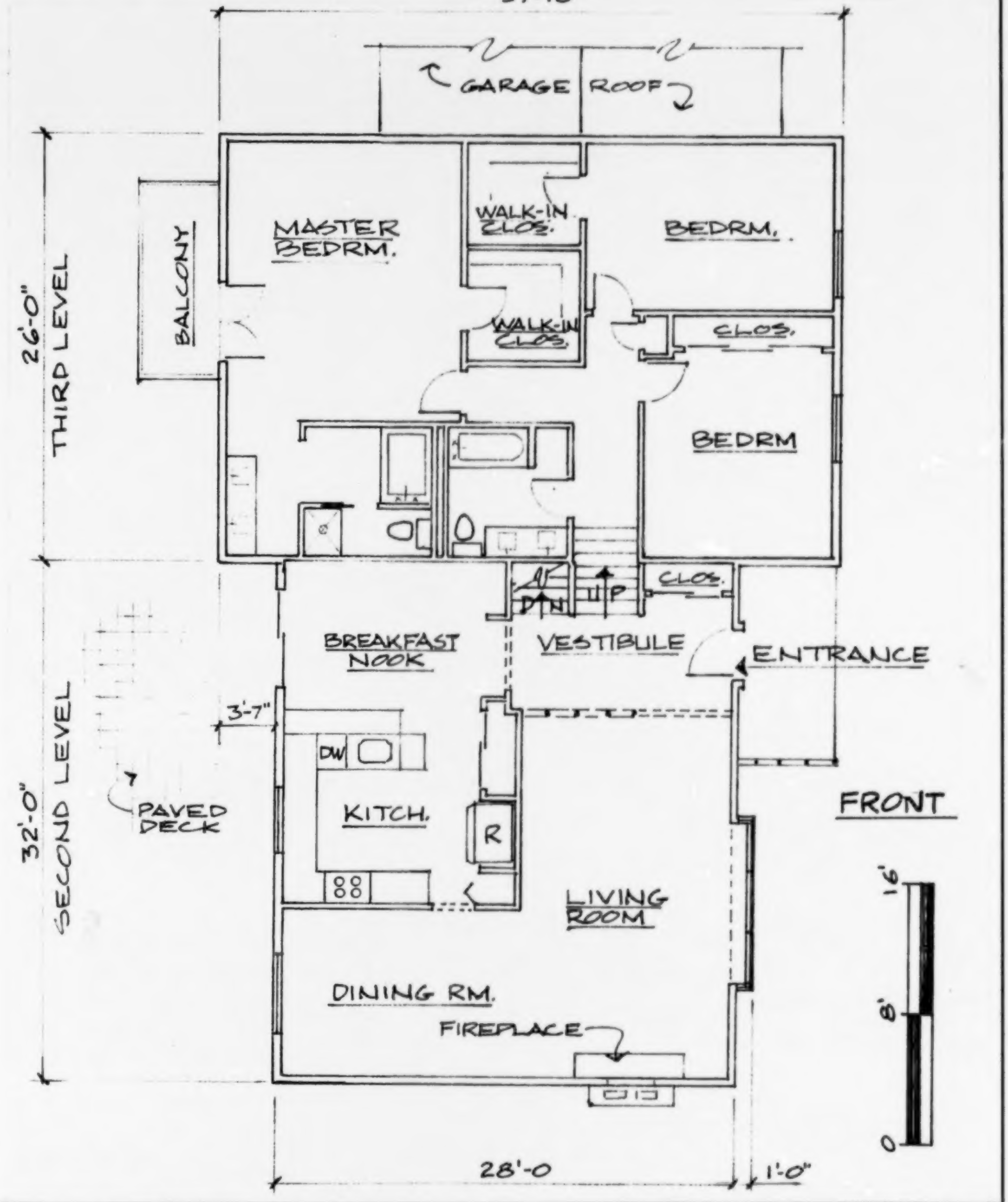
GRADE LEVEL PLAN

Date: 2/26/88

House Group: **PARTIAL BASEMENT**

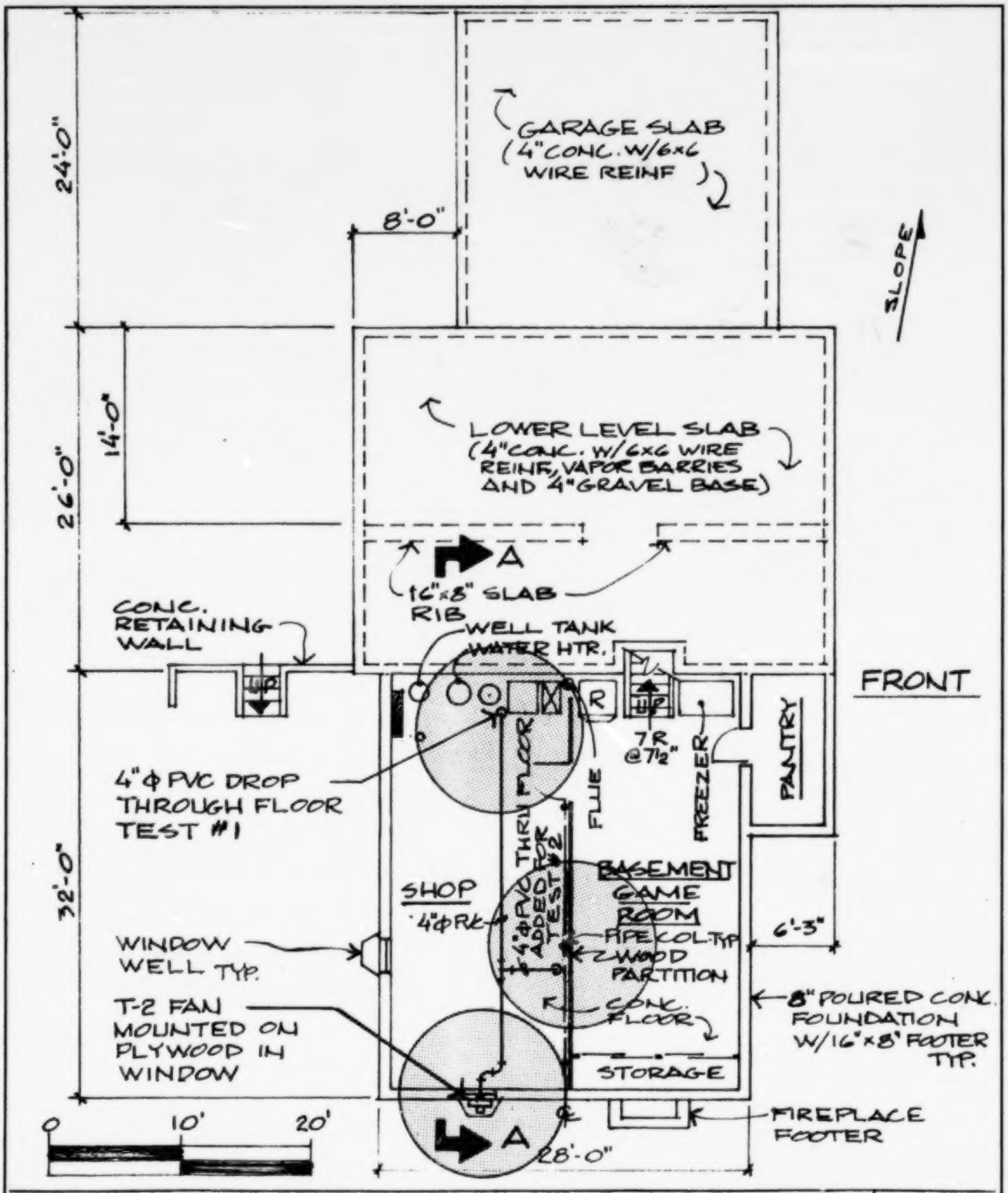
PHASE:

HOUSE NUMBER 11



ACRES
Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
SECOND & THIRD LEVEL PLAN	Date: 2/26/88	11
House Group: **PARTIAL BASEMENT**	PHASE:	



ACRES
Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON

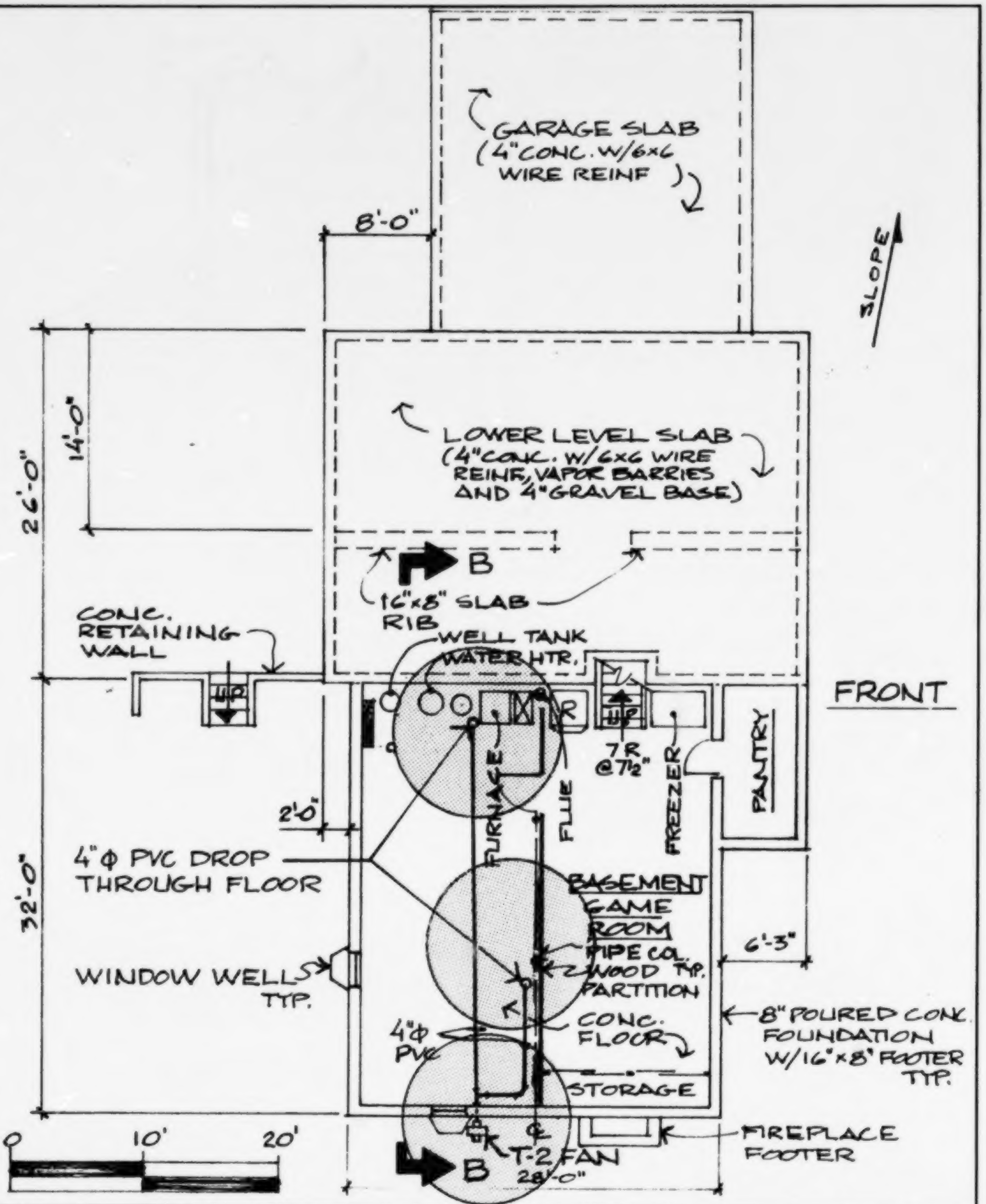
HOUSE NUMBER 11

BASEMENT/FOUNDATION PLAN

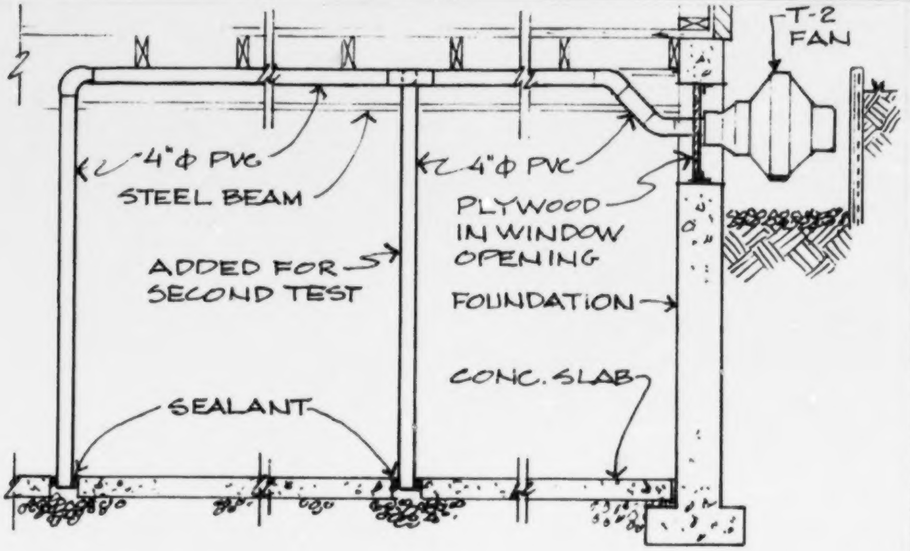
Date: MAY 1988

Mitigation system: SUB-SLAB SUCTION

PHASE: TEST 1&2

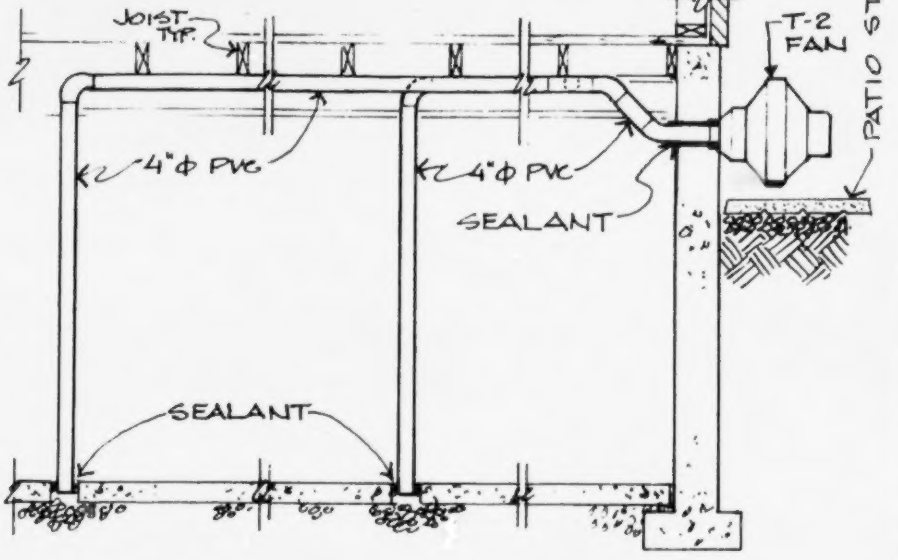


ACRES Acres International Corporation	LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
	BASEMENT/FOUNDATION PLAN	Date: MAY 1988	11
	Mitigation system: SUB-SLAB SUCTION	PHASE: Final	



SECTION A-A - TEST SYSTEM

N.T.S



SECTION B-B - FINAL SYSTEM

N.T.S

ACRES	**LOW COST REDUCTION OF INDOOR RADON**		HOUSE NUMBER
	SECTIONS/DETAILS	Date: MAY 1988	11
	Mitigation system: SUB-SLAB SUCTION	**PHASE:** TEST AND FINAL	

HOUSE 15

1 GENERAL DESCRIPTION

This small (90 m^2) slab-on-grade house with a detached garage was built in the late 1950's in a suburban subdivision in Xenia. The foundation wall is of poured concrete and the exterior walls are covered with metal siding. The floor in every room is completely covered with fitted carpet, applied over the original plastic tile. Heating is by a down-draft forced air gas furnace located centrally in a closet, with clay heat distribution ducts running radially beneath the floor slab to formed-concrete register boxes, closed with concrete at the bottom. There is a large opening through the floor slab beneath the bath, accessible via a coat closet by the front door. The sub-slab fill was visible at the bottom of the opening, and appeared to be a clean pea gravel, and a 12-mm layer of fiberglass sub-slab insulation was exposed at the edges of the hole.

2 INVESTIGATION

A short-term radon monitor survey was carried out in January 1988 as part of the pre-selection investigation. Radon concentrations ranged from 10 to 24 pCi/L, averaging 16.2 pCi/L over a period of 23 hours.

To investigate the role of the sub-slab heating ducts on the entry of soil gas and radon, the furnace fan was switched from normal cycling ("automatic") to continuous run. This would pressurize the sub-slab ducts and prevent the entry of soil gas, and also pressurize the sub-slab fill, which should reduce the movement of soil gas and radon towards the house. Prior to operation of the fan radon concentrations in the living room varied from 6 to 20 pCi/L, averaging 11.0 pCi/L. Over a 38-hour period with the central fan running continuously, the concentration ranged from 2 to 8 pCi/L, averaging 4.6 pCi/L (see Figure 15-1).

A second test was to close the large opening beneath the bath with expanding foam. With the fan on "Auto", concentrations over the 2 days prior to closing the opening ranged from 12 to 42 pCi/L, averaging about 25.5 pCi/L, and after closure ranged from 1 to 21 pCi/L, averaging 9.1 pCi/L (Figure 15-2).

Operation of the central fan continuously after closure of the opening under the bathtub resulted in indoor levels ranging from 0 to 2 pCi/L over 42 hours, averaging 1.1 pCi/L. Thus, it would appear that closure of the tub opening improved the effectiveness of continuous fan operation.

Radon concentrations beneath the floor slab were 100 pCi/L at hole 1 in the center of the slab, beside the furnace, and 30 pCi/L measured at hole 2, through an opening in a register box. The pressures at these holes went respectively from zero to 5 and 7 Pa when the furnace fan went from "off" to continuous run. When the opening below the bathtub was closed with expanding foam, the pressures with the fan operating were 16 and 8 Pa at holes 1 and 2.

3 MITIGATION

The mitigation system selected for demonstration at this house was sub-slab ventilation via the foundation wall. The system was planned in two stages: a temporary system to check the effectiveness of the system, followed by a permanent installation.

In early March 1988, a temporary system was installed from outside of the house. A 100-mm hole was core-drilled through the concrete perimeter wall at one end of the house, into the gravel fill directly beneath the floor slab. The sub-slab fiberglass insulation extended to the perimeter wall.

A sample of the fill was examined and found to be pit-run gravel, with a wide size distribution from 10-mm stones to sands and silt. The top of this material could appear to be a pea gravel, for moving and raking during placement would bring the large stones to the surface, but the permeability would be much less than a clean pea gravel.

A fan-in-a-box was connected to the opening by flex-duct attached to a toilet flange screwed onto the wall. With the fan operating at high speed, radon concentrations ranged from 0 to 1 pCi/L, averaging 0.3 pCi/L over 93 hours (Figure 15-4). When the fan was set to low speed, radon concentrations were similar, ranging from 0 to 1 pCi/L, averaging 0.2 pCi/L over a 61-hour period. The fan was returned to high speed, and the furnace fan was set to operate continuously. The radon concentration ranged from 0 to 1 pCi/L, averaging 0.1 pCi/L over 47 hours (Figure 15-6).

The furnace fan was returned to normal operation, and the sub-slab fan was reversed to test the effect of pressure ventilation. Radon concentrations ranged from 1 to 3 pCi/L, averaging 1.8 pCi/L over a 38-hour period. Clearly sub-slab pressurization was not as effective as suction.

A hand held power auger was used to drill a 2.1-m deep hole in the soil close to the house. The first 20 cm was an organic loam, underlain by a plastic sandy clay layer to a depth of about 1 m. The character of the clay changed then to a more sandy clay which was crumbled by the auger. Near the bottom of the hole (2.0 m), the clay again became slightly less sandy and more cohesive, and contained many small flat limestone rock fragments from 1 to 8 mm in diameter. A 4 inch plastic pipe was placed in the hole to keep it open.

Since the pattern of sub-slab heating ducts might control the effectiveness of sub-slab ventilation, a second exhaust hole was made in the opposite foundation wall. The temporary ventilation system was then installed and the first hole was taped closed. In this new location the fan ran at a maximum speed drawing 70 pCi/L air at a flow rate of 20 L/s. At the same time the radon concentration in the auger hole pipe was 75 pCi/L. The radon concentrations ranged from 0 to 1 pCi/L and averaged 0.5 pCi/L over 37 hours. Essentially the same results were obtained when the furnace fan was set to continuous run, with radon concentrations ranging from 0 to 1 pCi/L, averaging 0.4 pCi/L over 19 hours.

4 FINAL INSTALLATION

It was agreed with the owner that the permanent installation would be made at the original location. This was accomplished in late May 1988. A T-2 fan mounted on a wood panel was placed over the opening, and a permanent electrical supply provided. The second hole was cemented over.

5 OTHER MEASUREMENTS

The 1987 charcoal canister test gave a value of 26.6 pCi/L, but this was measured in the floor slab opening beneath the bath. A short term radon monitor survey found radon concentrations in the living room ranged from 10 to 24 pCi/L, averaging 16.2 pCi/L.

A pre-mitigation alpha-track measurement over the period December 1987 to February 1988 gave average radon concentrations of 16.2 pCi/L in the living area.

A post-mitigation Alpha-track measurement over the period May to August 1988 gave an average radon concentration of 2.4 pCi/L in the living area.

The radiation field in the house ranged from 3 to 6 μR/h over the entire floor slab. The field over the site outside the house ranged from 4 to 7 μR/h, averaging 6 μR/h.

MEASUREMENTS SUMMARY FOR HOUSE 15

PYLON AB-5 HOURLY MONITORING

MITIGATION SYSTEM	TEST DATE	TEST STATUS	RADON(pCi/L) RANGE	MEAN	MONITOR DURATION*	FIG.
pre-selection**	01/88		11-24	16.2	23 hrs	
sub-slab pressurization using central HVAC fan	02/88	fan cycling, on auto	6-20	11.0	48 hrs	15-1
		fan on contin.	2- 8	4.6	38 hrs	15-1
bath-tub opening foamed closed	02/88	before	12-42	25.5	49 hrs	15-2
		after	1-21	9.1	43 hrs	15-2
sub-slab pressure (HVAC fan)	02/88	on continuously	0- 2	1.1	42 hrs	15-3
		on auto	2-18	8.4	42 hrs	15-3
sub-slab suction (exterior fan)	03/88	DPmax; auto	0- 1	0.3	93 hrs	15-4
		DPmax; auto	0- 1	0.6	32 hrs	15-5
		0.5DPmax; auto	0- 1	0.2	61 hrs	15-5
sub-slab suction	04/88	DPmax; HVAC on continuously	0- 1	0.1	47 hrs	15-6
sub-slab pressure	04/88	DPmax; HVAC on automatic	1- 3	1.8	38 hrs	15-6
sub-slab suction (new exterior fan location)	04/88	DPmax; auto	0- 1	0.5	37 hrs	15-7
		DPmax; cont.	0- 1	0.4	19 hrs	15-7

* The monitoring duration and the radon concentrations shown in this table generally exclude the first 5 hours of Pylon data collected immediately after a change in system conditions.

** RAPCA femto-TECH R210F used

Average pre-mitigation Pylon results (presented in Tables IX, X, XI and 3):
Weighted average of the femto-TECH pre-selection results and the pre-mitigation portions of Figures 15-1 and 15-2 (HVAC on auto) (120 hours total) = 17.9 pCi/L.

Average post-mitigation Pylon results:
Furnace fan on continuously — Fig. 15-1 (38 hrs total) = 4.6 pCi/L.
Bathtub opening closed — Fig. 15-2 ("after") and HVAC auto portion of 15-3 (85 hrs) = 8.8.
Furnace fan on after tub closure — Fig. 15-3 (42 hrs) = 1.1 pCi/L
Sub-slab suction, fan at DPmax — HVAC auto portion of Fig. 15-7 (37 hr) = 0.5 pCi/L

SYSTEMS MEASUREMENTS

PHASE	MITIGATION SYSTEM	TEST DATE	MEASUREMENTS			COMMENT
			SUCTION (Pa)	FLOW (L/s)	RADON (pCi/L)	
1	sub-slab pressure (HVAC fan)	02/88	-5*		100	hole 1; cont. run
			-7		30	hole 2; cont. run
			-16			hole 1; (bath tub
			-8			hole 2; foamed)
1	sub-slab suction (exterior fan)	03/88	340			at fan; DPmax
			190		100	at fan; 0.5DPmax
1	sub-slab suction (new suction location)	04/88	290	20	70	at fan; DPmax
					75	ground riser

* "Negative suction" denotes pressurization relative to house.

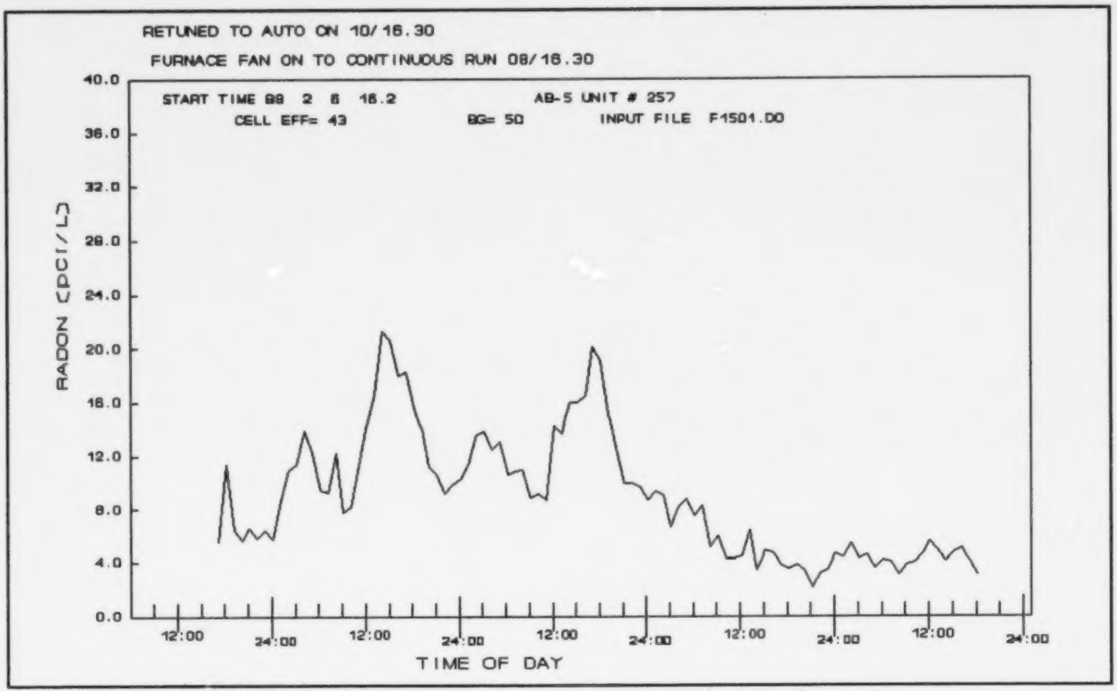


Figure 15-1. Central furnace fan cycling normally vs. operating continuously

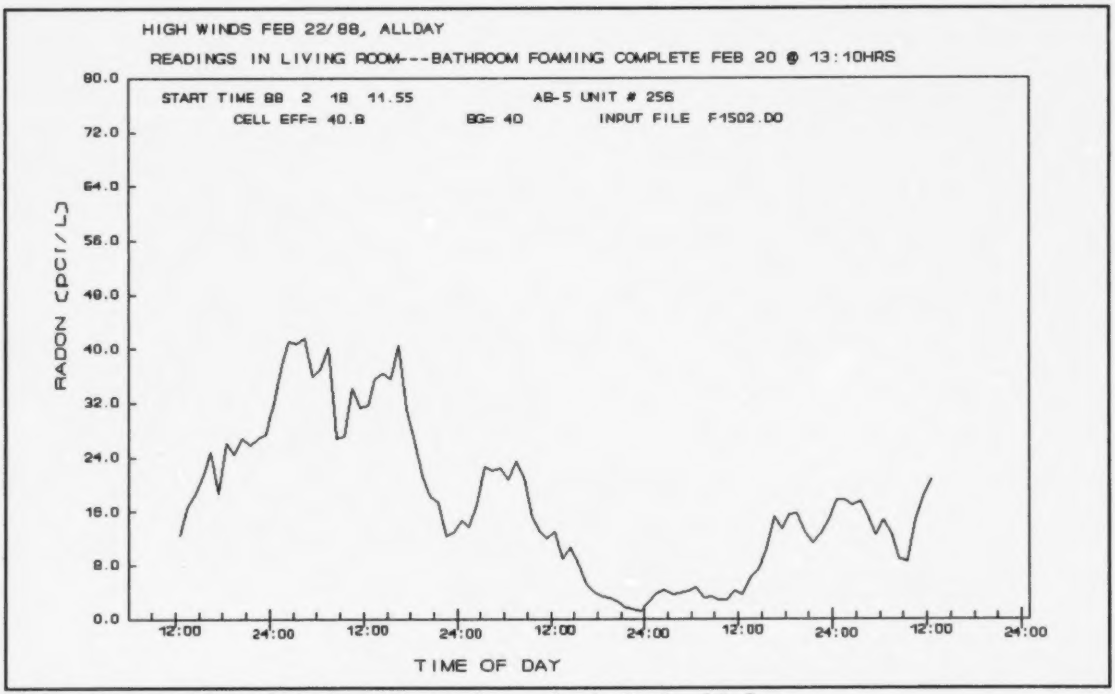


Figure 15-2. Effect of closing slab opening under bathtub with foam

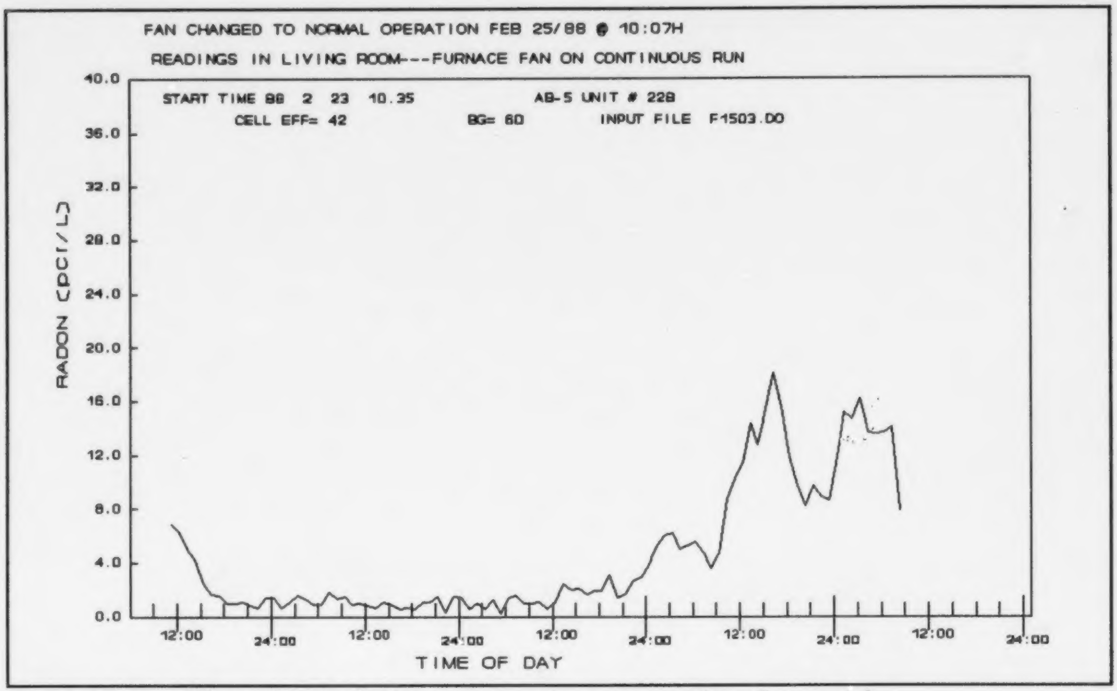


Figure 15-3. Effect of bathtub closure on continuous operation of central fan

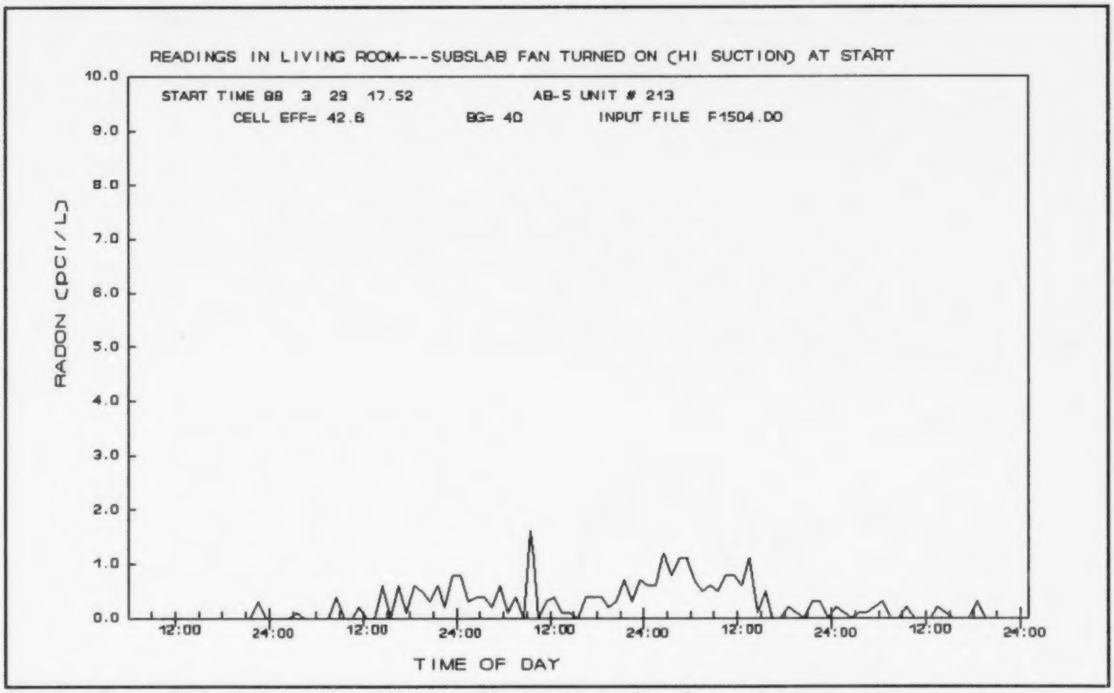


Figure 15-4. Sub-slab suction with exterior suction point, fan at DPmax

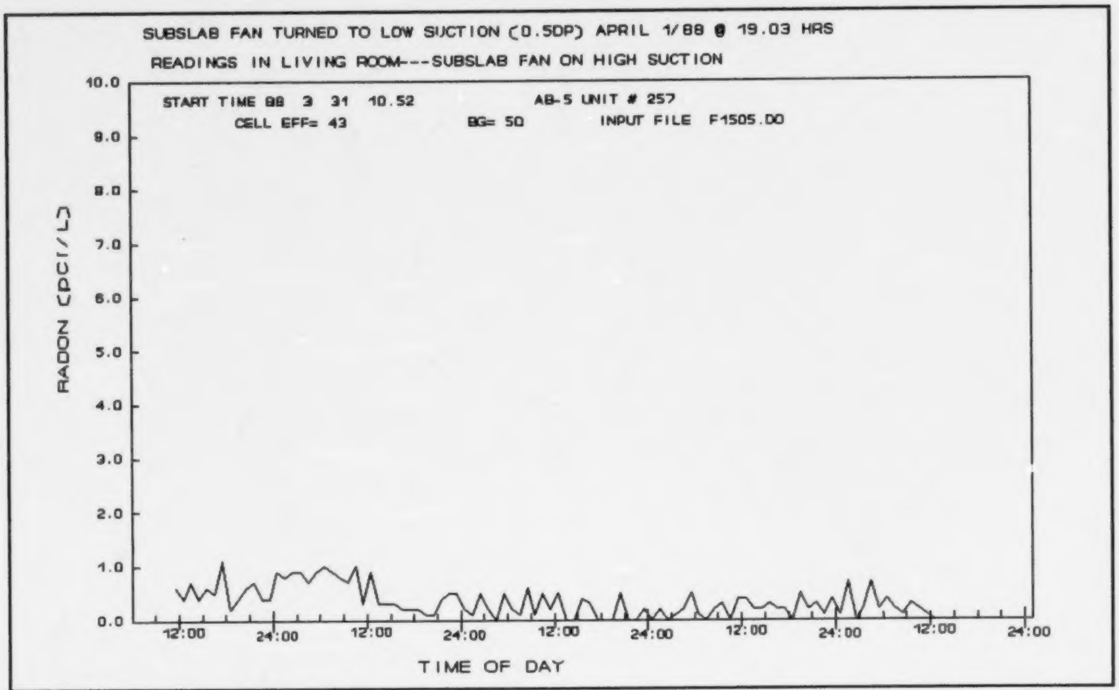


Figure 15-5. Effect of mitigation fan speed on sub-slab suction

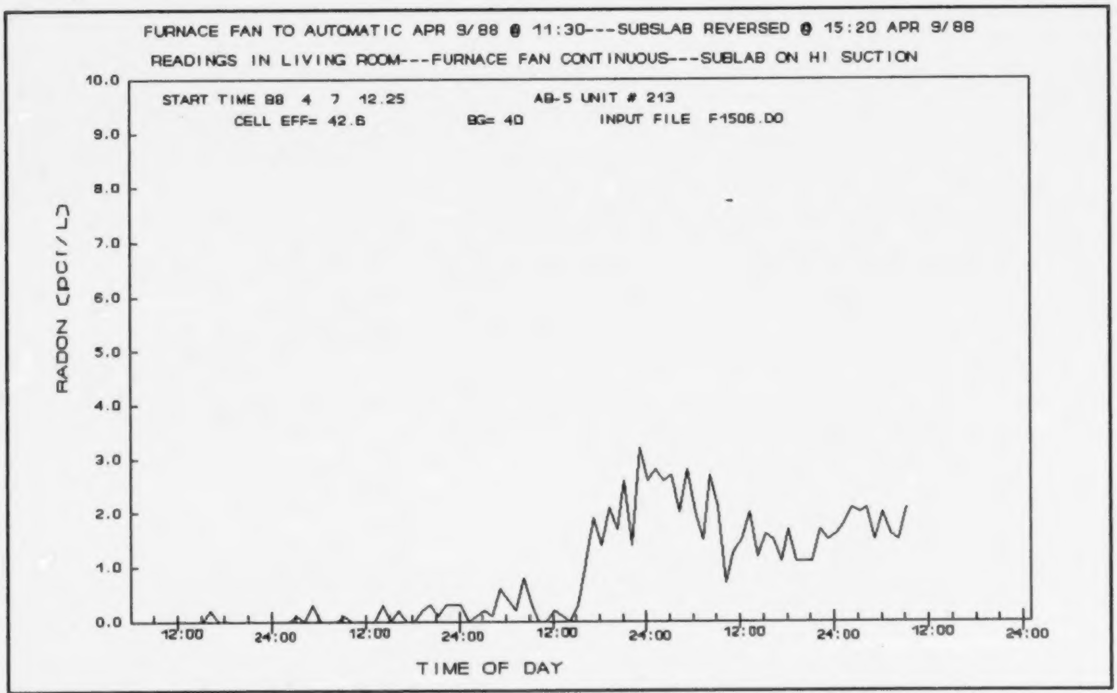


Figure 15-6. Effect of central fan operation, and of sub-slab pressurization vs. suction

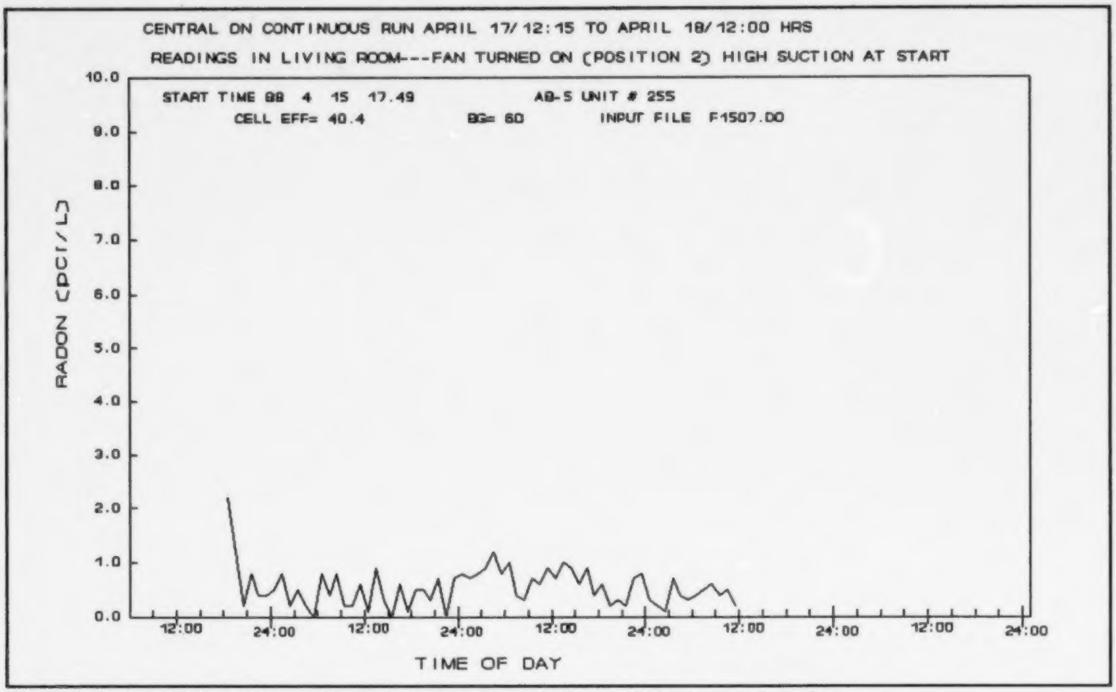
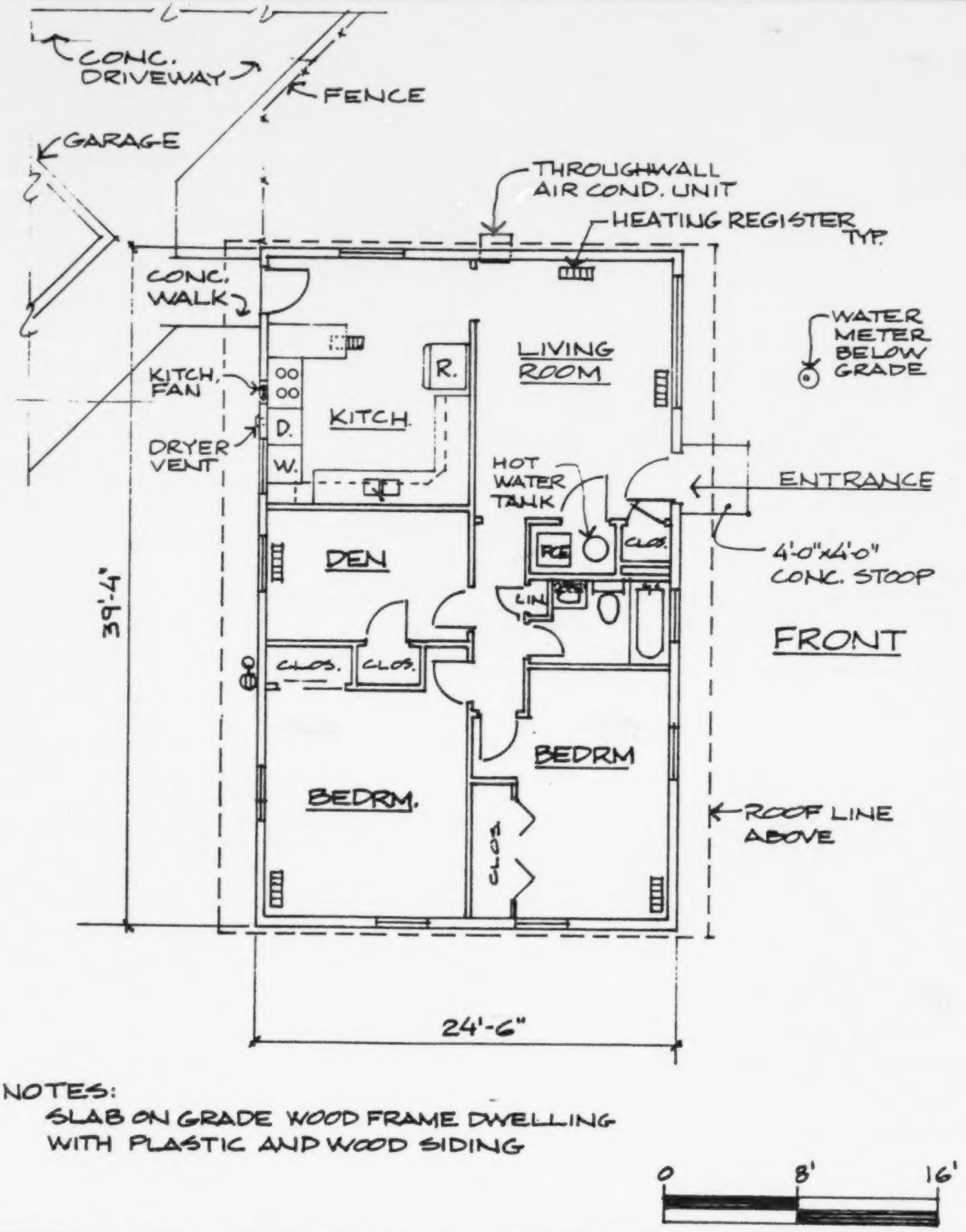
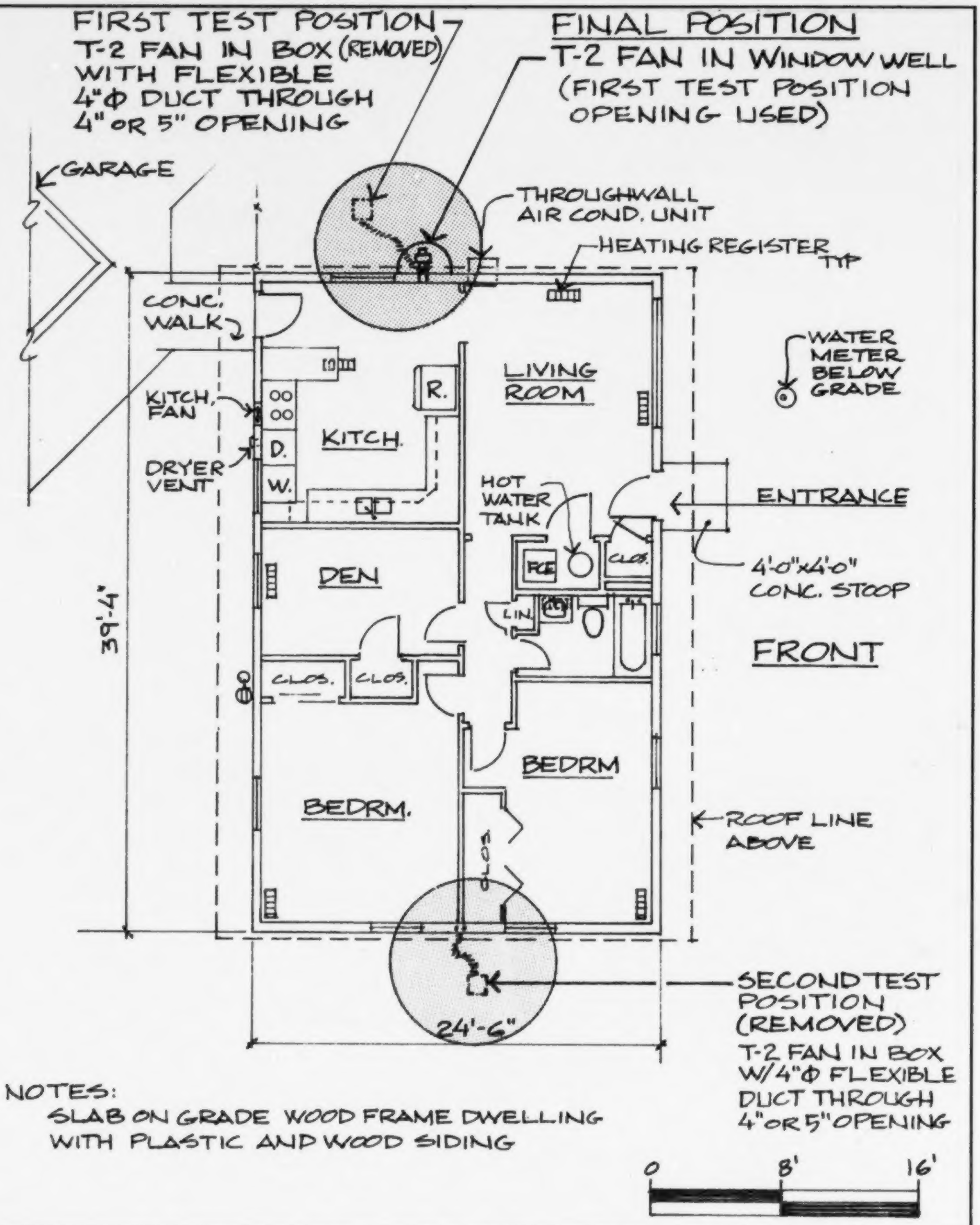


Figure 15-7. Sub-slab suction with exterior suction point at new location



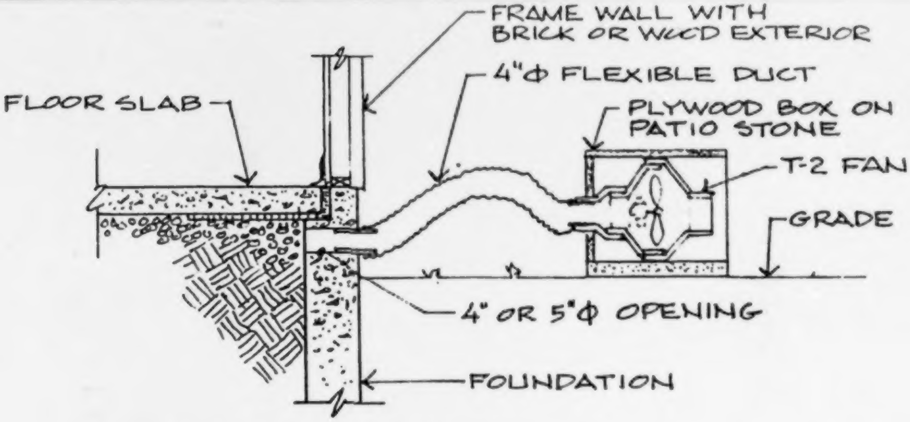
NOTES:
SLAB ON GRADE WOOD FRAME DWELLING
WITH PLASTIC AND WOOD SIDING

ACRES Acres International Corporation	LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
	GRADE LEVEL PLAN	Date: 2/22/88	15
	House Group: SLAB ON GRADE	PHASE:	



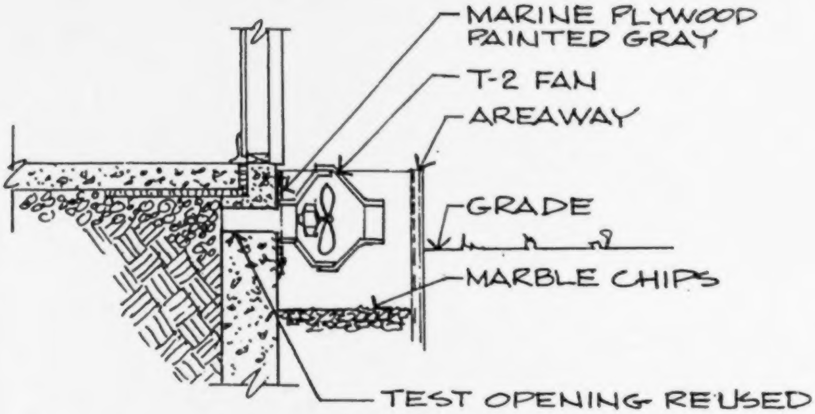
NOTES:
SLAB ON GRADE WOOD FRAME DWELLING
WITH PLASTIC AND WOOD SIDING

ACRES Acres International Corporation	**LOW COST REDUCTION OF INDOOR RADON**		**HOUSE NUMBER**
	GRADE LEVEL PLAN	Date: MAY 1988	15
	Mitigation system: SUB-SLAB SUCTION	PHASE: TEST AND FINAL	



TEST POSITIONS

N.T.S.



FINAL POSITION

N.T.S.

ACRES Acres International Corporation	LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
	SECTIONS/DETAILS	Date: MAY 1988	15
	Mitigation system: SUB-SLAB SUCTION	PHASE: TEST AND FINAL	

HOUSE 21

1 GENERAL DESCRIPTION

This large (170 m^2) two-story slab-on-grade house with an attached garage was built in the mid 1960's in a suburban subdivision in the south of Xenia. The foundation wall is of poured concrete. The exterior walls are of brick. The floor is completely covered with fitted carpet, applied over the original tile. Heating is by a down-draft forced air gas furnace located centrally in a closet, with clay heat distribution ducts running radially beneath the slab-on-grade floor slab to formed concrete register boxes. The boxes are closed with concrete at the bottom.

The owner has modified the house by turning the garage into a family room, and as part of this process, removed the garage floor slab, and excavated a small basement/tornado shelter in this area. The family room has a wooden suspended floor, which forms the roof of the adjoining basement/tornado shelter. (The central area of Xenia was destroyed by a tornado in 1974). The basement walls are of concrete block, with reinforcing bar and concrete placed in the block voids, and the floor is a concrete slab. The front and rear basement walls are placed underneath the poured concrete foundation walls for the garage, but the side walls are set in from the foundation walls by 700 mm. There is a dry sump without a sump pump and without drain tiles in the rear of the basement. The sump crock is a 800 mm long concrete sewer pipe, and gravel is visible at the bottom of the sump.

The owner had a photograph of the house under construction, which clearly showed that the heating ducts were made of 600 mm lengths of clay tile, butted end to end, and lying directly on the stripped soil surface inside the foundations. The pea-gravel fill (used to support the floor slab) had been poured into a pile over the top of one set of pipes, and was being raked out to level with the top of the pipes. The owner said that a plastic sheet was placed over the fill, and then the concrete floor slab was poured. As the heat ducts in this house rested on clay, and had the floor slab touching the top, they could be expected to divide the sub-floor space up into a number of independent compartments.

2 INVESTIGATION

A sub-slab permeability and connectivity test was carried out in the basement portion of the house as part of the EPA pre-selection process in January 1988. The owner said that there was no sub-slab fill, and the floor was poured directly on to the gravel exposed by the excavation. A 30-mm hole was drilled at the end of the basement near the stairs and three 12-mm holes (1, 2 and 3) were drilled at distances of 0.3,3, and 5 m. When a suction of 3400 Pa was applied at the large hole, suctions of 200, 59, and 22 Pa were detected at holes 1, 2 and 3 respectively. The undisturbed sub-slab radon levels of 1000 and 910 pCi/L were measured at holes 2 and 3. By comparison, the concentration in the basement at that time was 70 pCi/L and in an upstairs bedroom was 25 pCi/L, based upon grab samples.

A short-term radon-monitor survey conducted in January 1988 as part of the pre-selection program found radon levels in the upstairs dining room ranged from 5 to 16 pCi/L and averaged 11.4 pCi/L over a 96-hour period.

To investigate the effect of closing the major openings to the soil, the exposed gravel at the base of the sump was covered with a layer of expanding urethane foam. A water-filled syphon fabricated from a plastic bottle and a tube was placed in the bottom of the sump to allow water to drain from the sump without allowing entry of soil gas. The foam continued to expand, and closed off the syphon, so the sump was partly filled with condensate from the dehumidifier.

Prior to closing the sump, radon concentrations in the basement ranged from 70 to 187 pCi/L, averaging 125.1 pCi/L, and afterwards ranged from 49 to 159 pCi/L, averaging 101.4 pCi/L (Figure 21-3). Radon concentrations in the dining room before closing the sump ranged from 8 to 27 pCi/L, averaging 15.4 pCi/L. Afterwards, levels ranged from 3 to 17 pCi/L, averaging 10.8 pCi/L (Figure 21-2). The ratio of upstairs to basement concentrations over this period was approximately 1 to 10, comparable to the inverse volume ratio, suggesting that most of the radon that entered the basement found its way into the house.

The radon concentration in the fill under the slab-on-grade wing, measured through an opening at the bathroom register, was 4 pCi/L. No effective difference was noted in the pressure induced at the register by running the HVAC fan continuously before (17 Pa) sump foaming and after (18 Pa).

As a further test of closing major openings, two days later the opening in the house floor slab beneath the bath on the slab on grade was filled with expanding foam. After this closure, the radon concentration in the dining room varied from 5 to 10 pCi/L, averaging 7.1 pCi/L, but basement concentrations were lower too, averaging 83.6 pCi/L. There was no significant change in the upstairs/basement ratio of radon concentrations as a result of the tub closure.

This suggested that if the basement radon concentrations could be reduced to a few pCi/L, then the concentrations in the rest of the house would be reduced to low levels.

3 MITIGATION

The mitigation system selected for demonstration was sub-slab soil ventilation, utilizing the unused sump hole in the basement (which connected to no drain tiles) to provide convenient access through the slab. The system was planned in two stages: a temporary system to check the effectiveness of the system, followed by a permanent installation. Only the basement portion would be treated at first, and the slab-on-grade portion of the house would be treated only if the reduction in radon concentration was insufficient.

In mid-March 1988, the foam was removed from the sump and a sump cover constructed of lucite with a 2-inch drain and a short section of 4-inch pipe was installed. A temporary ventilation system was installed with T-2 fan and speed control in the attic, with the discharge via an existing attic vent in the soffit.

Before the foam was removed, a 30 mm diameter tube was inserted through the foam, and an industrial vacuum cleaner was used to apply suction beneath the foam. At a suction of 4900 Pa, suctions of 200 and 54 Pa were detected at holes 1 and 2, but no effect was noticed at the bathroom register. With the vacuum off the natural pressure difference across the slab was noted as varying from 2 to 5 Pa.

When the system fan was working at high suction (250-290 Pa) and a flow of 6 L/s, suctions of 51 and 10 Pa were found at holes 1 and 2. Basement radon concentrations ranged from 2 to 6 pCi/L, averaging 4.0 pCi/L over 89 hours under these conditions (Figure 21-7), but ranged from 62 to 98 pCi/L, averaging 83.2 pCi/L over 52 hours when the fan was turned off (Figure 21-6). The radon in the fan air was initially measured at 750 pCi/L, and 5 days later was 525 pCi/L.

The fan suction was reduced to 110 Pa and the flow rate to 2 L/s, upstairs radon concentrations ranged from 0 to 2 pCi/L and averaged 0.9 pCi/L over 95 hours.

4 FINAL INSTALLATION

During the second week of April 1988, the sump ventilation system was made permanent. The sump cover was caulked in place, flexible hose was replaced by plastic pipe and the T-2 in-line fan was positioned to exhaust through the roofline cupola in the garage roof instead of the eaves. With the fan providing a flow of 7 L/s and a suction of 320 Pa at the sump, basement radon concentrations ranged from 1 to 4 pCi/L averaging 2.4 pCi/L over 70 hours, while upstairs radon ranged from 0 to 2 pCi/L averaging 0.7 pCi/L over 70 hours.

5 OTHER MEASUREMENTS

The 1987 charcoal canister test gave a value of 93.0 pCi/L in the basement. A short term radon monitor survey found that the radon concentration in the living room varied from 5 to 16 pCi/L, averaging 11.4 pCi/L.

Pre-mitigation alpha-track measurements over the period December 1987 to February 1988 gave average radon concentrations of 12.7 pCi/L in the living area and 98.6 pCi/L in the basement.

Post-mitigation alpha-track measurements over the period May to August 1988 gave an average radon concentrations of 1.4 pCi/L in the living area and 4.4 pCi/L in the basement.

The radiation field in the house ranged from 4 to 6 μR/h over the entire upper floor slab and 7 to 8 μR/h over the basement floor slab. The field over the site outside the house ranged from 5 to 7 μR/h, averaging 6 μR/h.

MEASUREMENTS SUMMARY FOR HOUSE 21

PYLON AB-5 HOURLY MONITORING

MITIGATION SYSTEM	TEST DATE	TEST STATUS	RADON(pCi/L) RANGE	MEAN	DURATION/ LOCATION	FIG.
pre-selection	01/88		6-16	11.4	96 hrs; U*	21-1
sump closure	02/88	before	70-187	125.1	42 hrs; B*	21-3
		after	49-159	101.4	47 hrs; B	21-3
		before	8- 27	15.4	43 hrs; U	21-2
		after	3- 17	10.8	46 hrs; U	21-2
bath-tub opening foamed	02/88	after	68-107	83.6	41 hrs; B	21-5
		after	5- 10	7.1	41 hrs; U	21-4
sub-slab suction via sump hole	03/88	fan off	64-98	83.2	52 hrs; B	21-6
		on; DPmax	2- 6	4.0	89 hrs; B	21-7
		on; 0.5DPmax	0- 2	0.9	95 hrs; U	21-8
sub-slab suction via sump hole (permanent)	04/88	on; DPmax	0- 2	0.7	70 hrs; U	21-9
		on; DPmax	1- 4	2.4	70 hrs; B	21-10

* B=Basement; U=Upstairs

Average pre-mitigation Pylon results (presented in Tables VIII and 3):

Basement
Average of pre-mitigation portion of Figure 21-3 (42 hours) = 125.1 pCi/L.

Slab on grade
Weighted average of Figure 21-1 and pre-mitigation portion of Figure 21-2 (139 hours total) = 12.6 pCi/L.

Average post-mitigation Pylon results (sub-slab suction with fan at DPmax, presented in Table VIII):

Basement
Average of Figure 21-7 (89 hours) = 4.0 pCi/L.

Slab on grade
Average of Figure 21-8 (95 hours) = 0.9 pCi/L.
Post-mitigation data for slab on grade are with fan at 0.5 DPmax, because data at DPmax are not available. Data from Figures 21-9 and 21-10 are not used in this calculation because those measurements were made in late April, after the weather had turned mild.

SYSTEMS MEASUREMENTS

PHASE	MITIGATION SYSTEM	TEST DATE	MEASUREMENTS			COMMENT
			SUCTION (Pa)	FLOW (L/s)	RADON (pCi/L)	
1	pre-selection	01/88	3400			suction at slab
			200			at hole 1
			59		1000	at hole 2
			22		910	at hole 3
					70	basement air
					25	upstairs bedroom
1	sump closure by foaming (HVAC on continuously)	02/88	17		4	at register;before
			18			at register; after
1	bath-tub opening foamed (HVAC on continuously)	02/88	9			at register; after
1	sub-slab suction via sump	03/88	4900			suction at sump
			200			at hole 1
			54			at hole 2
			0			at register
			2-5			natural DP at slab
			250-290	6	750	at riser; DPmax
					525	ditto;5 days later
			51			at hole 1
			10			at hole 2
			110	2		at riser; 0.5DPmax
1	sub-slab suction via sump(permanent)	04/88	320	7		at riser; DPmax

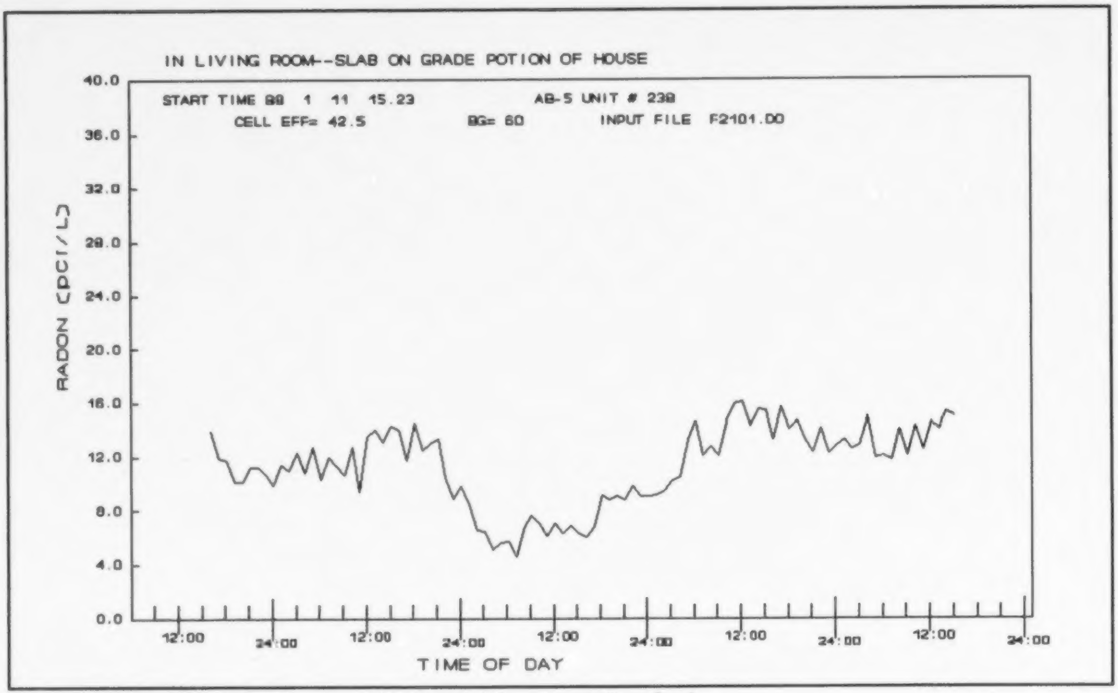


Figure 21-1. Pre-selection monitoring (slab-on-grade wing)

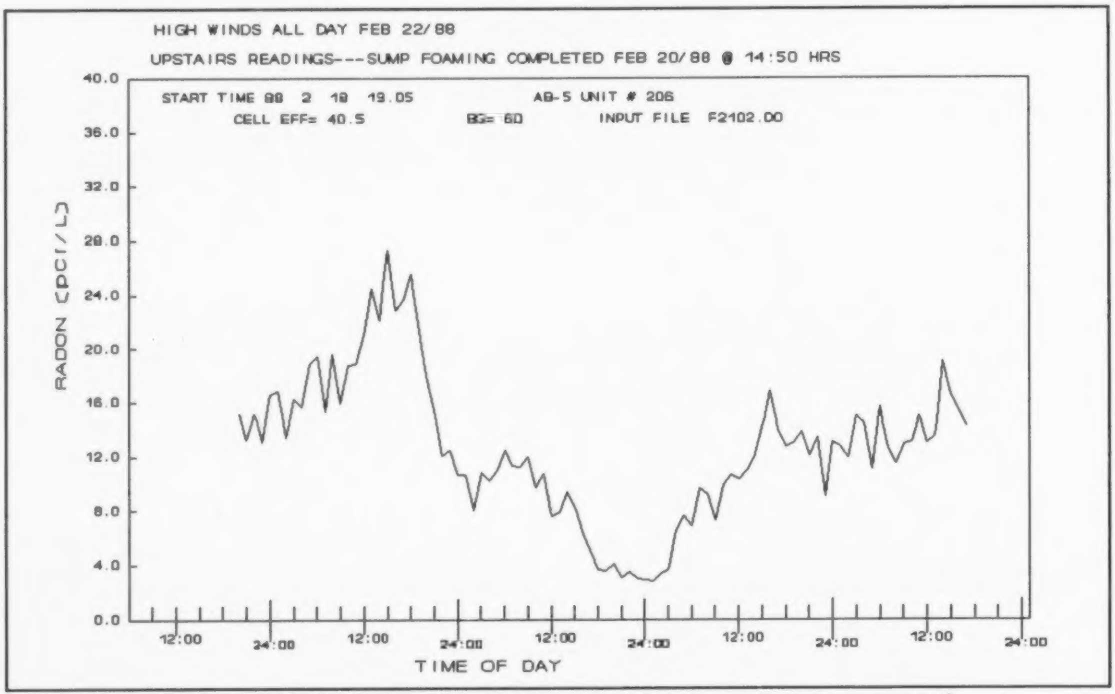


Figure 21-2. Effect of closing sump hole in basement (slab on grade measurements)

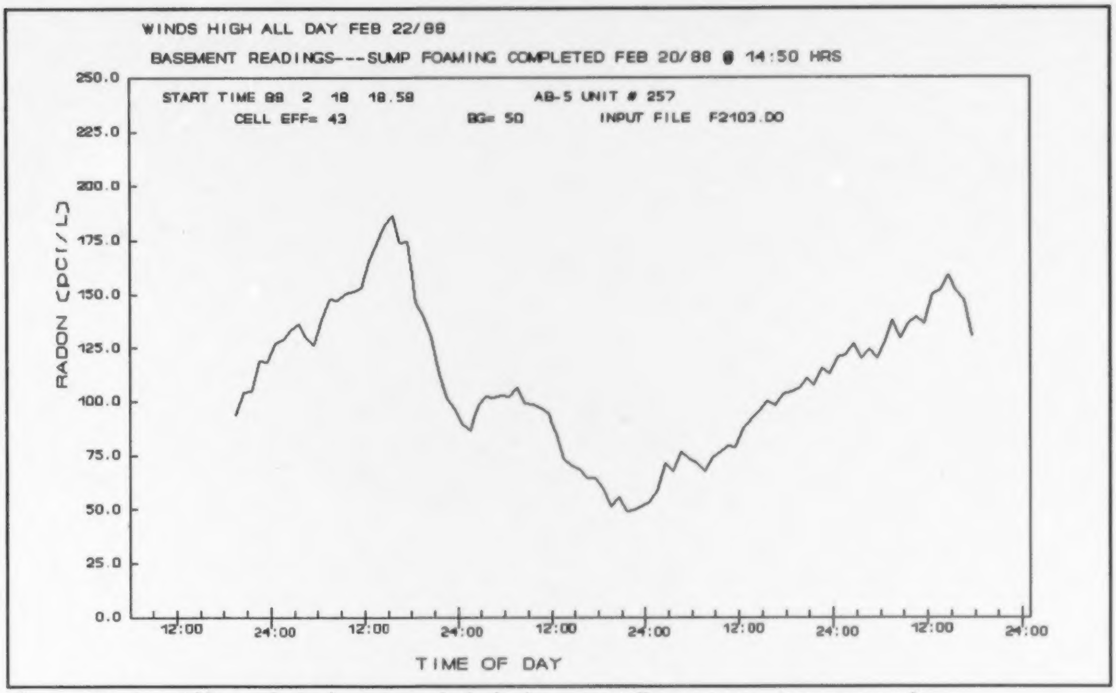


Figure 21-3. Effect of closing sump hole in basement (basement measurements)

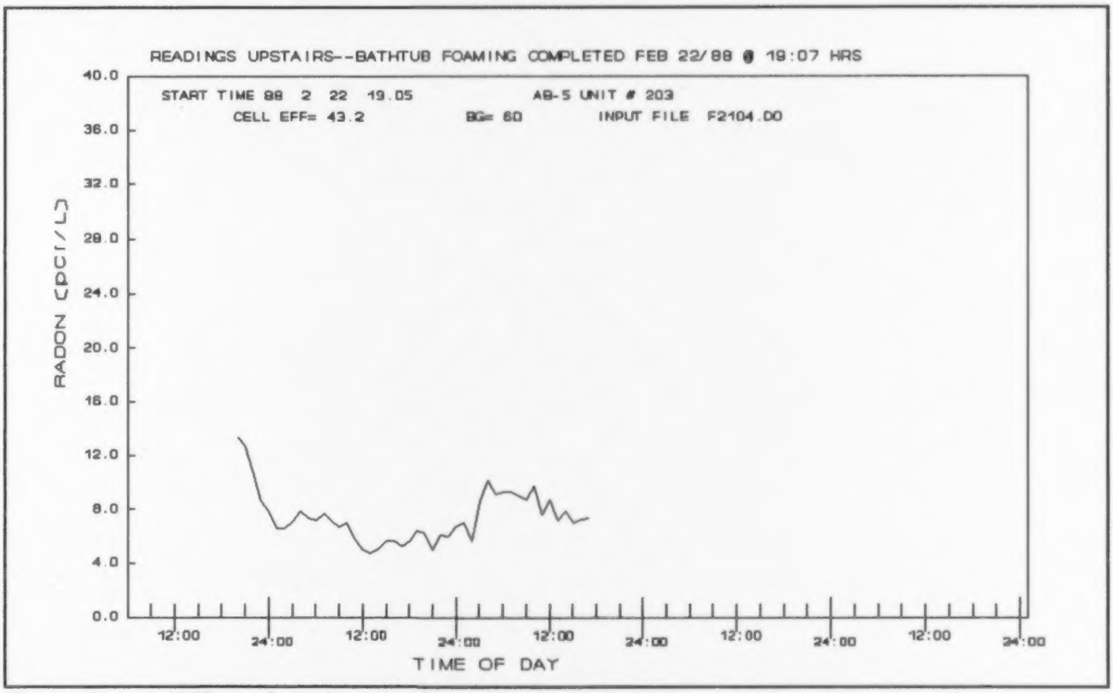


Figure 21-4. Effect of closing opening under bathtub (slab on grade measurements)

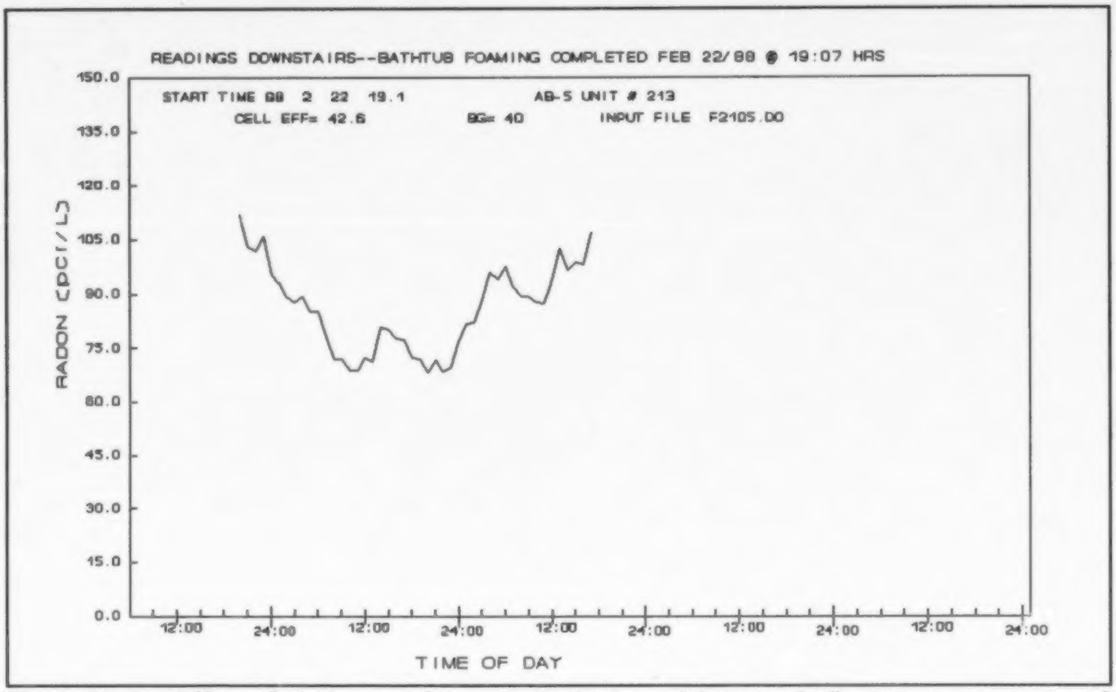


Figure 21-5. Effect of closing opening under bathtub on slab on grade (basement measurements)

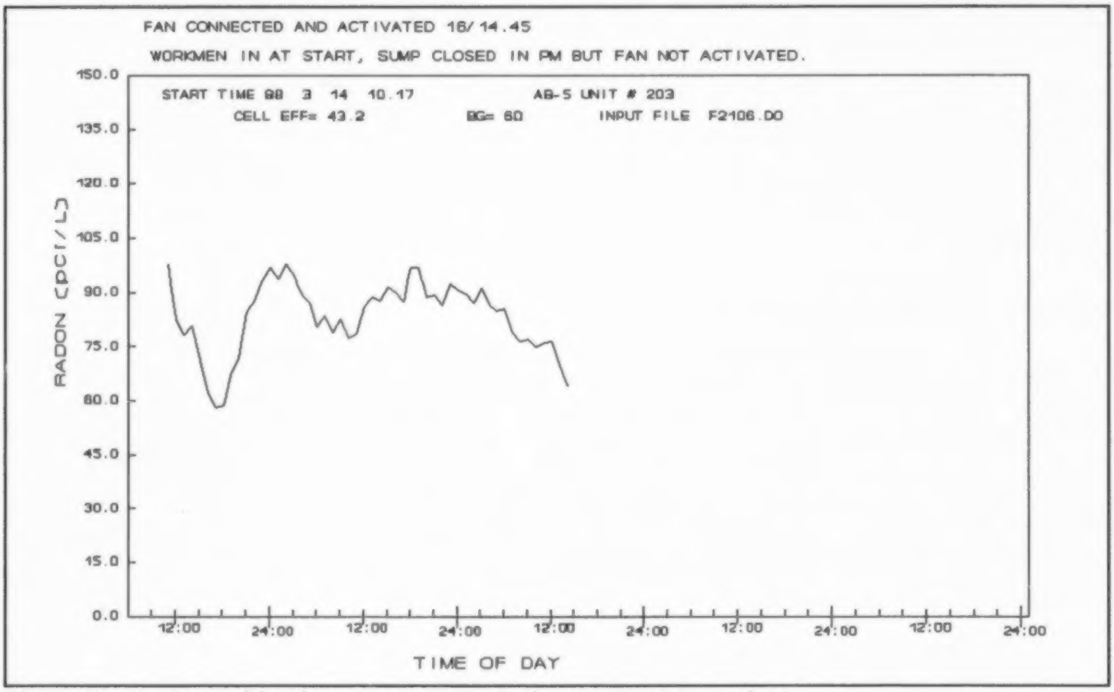


Figure 21-6. Pre-mitigation measurement (prior to sub-slab suction)

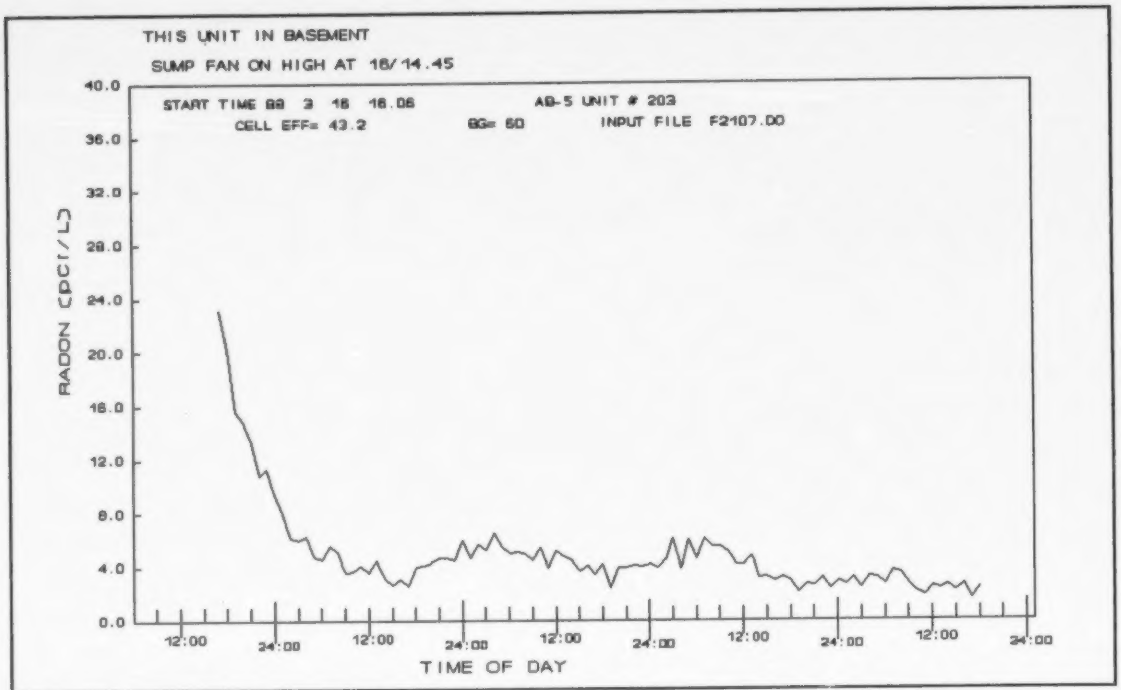


Figure 21-7. Sub-slab suction in basement, fan at DPmax (basement measurement)

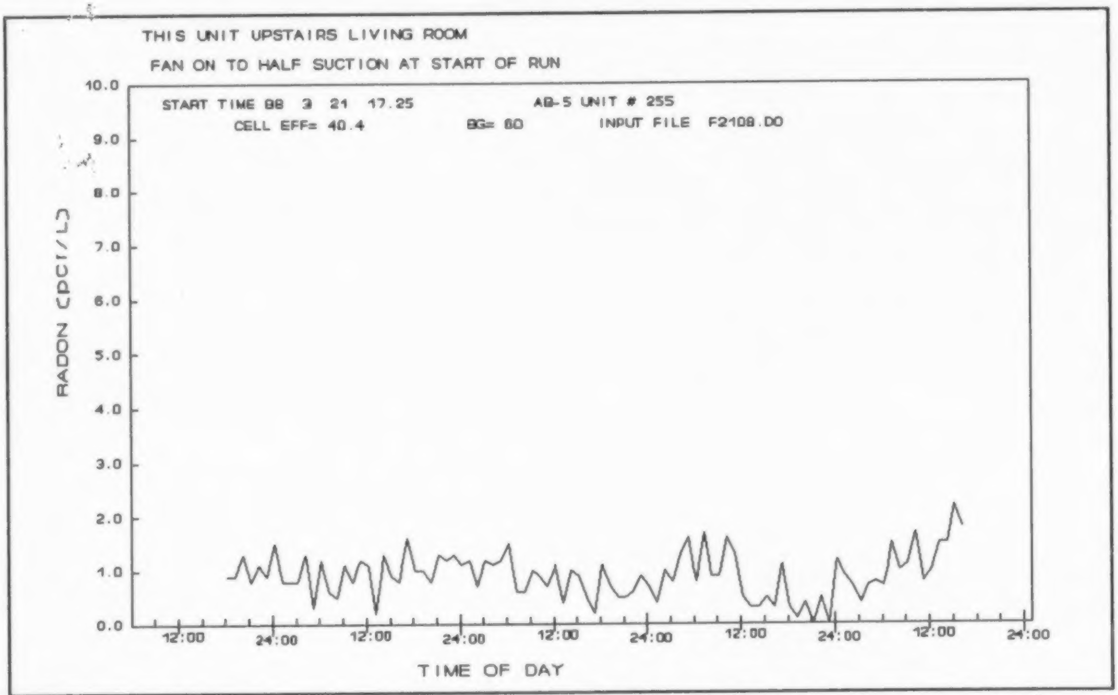


Figure 21-8. Sub-slab suction in basement, fan at 0.5 DPmax (slab on grade measurement)

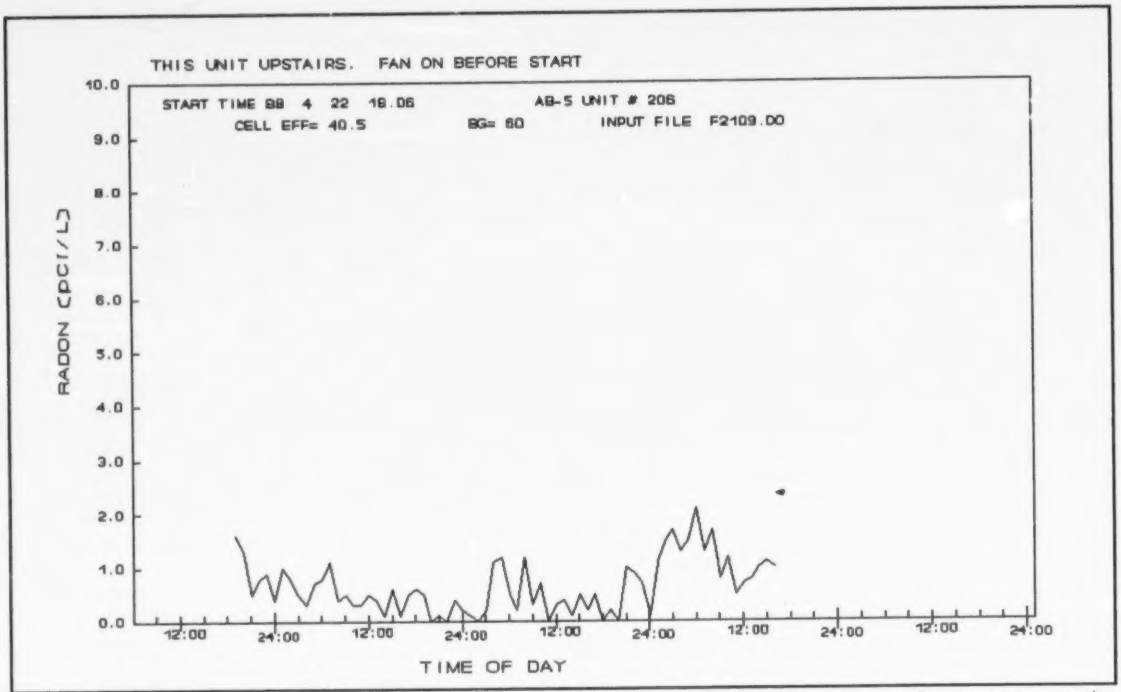


Figure 21-9. Sub-slab suction in basement, permanent installation (slab on grade measurement)

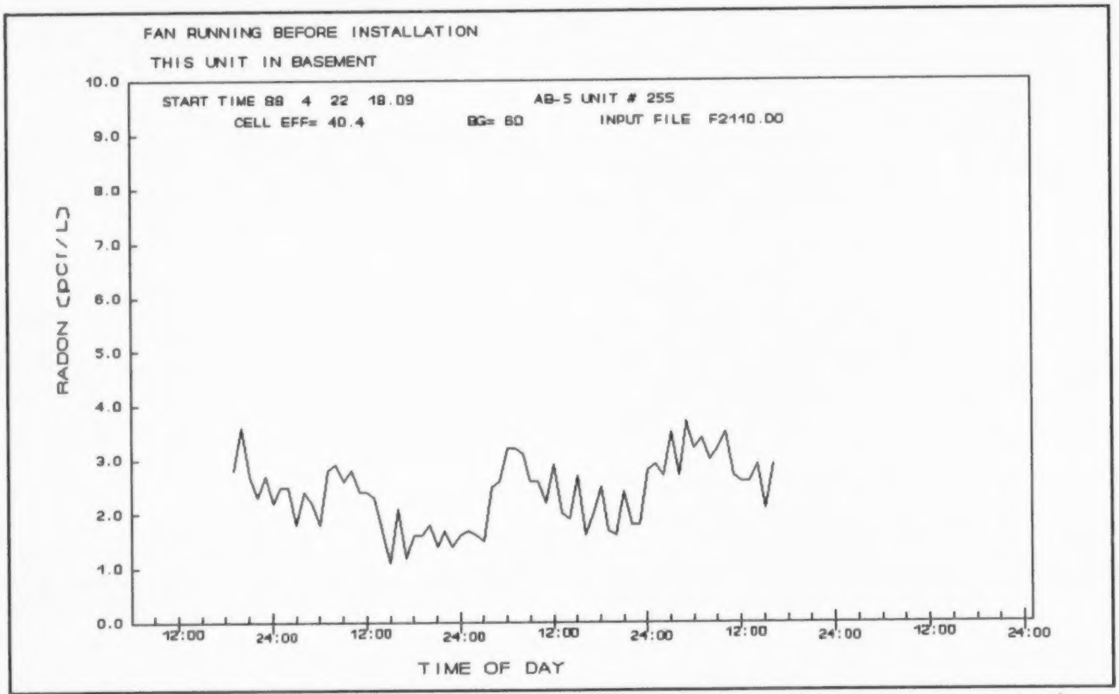
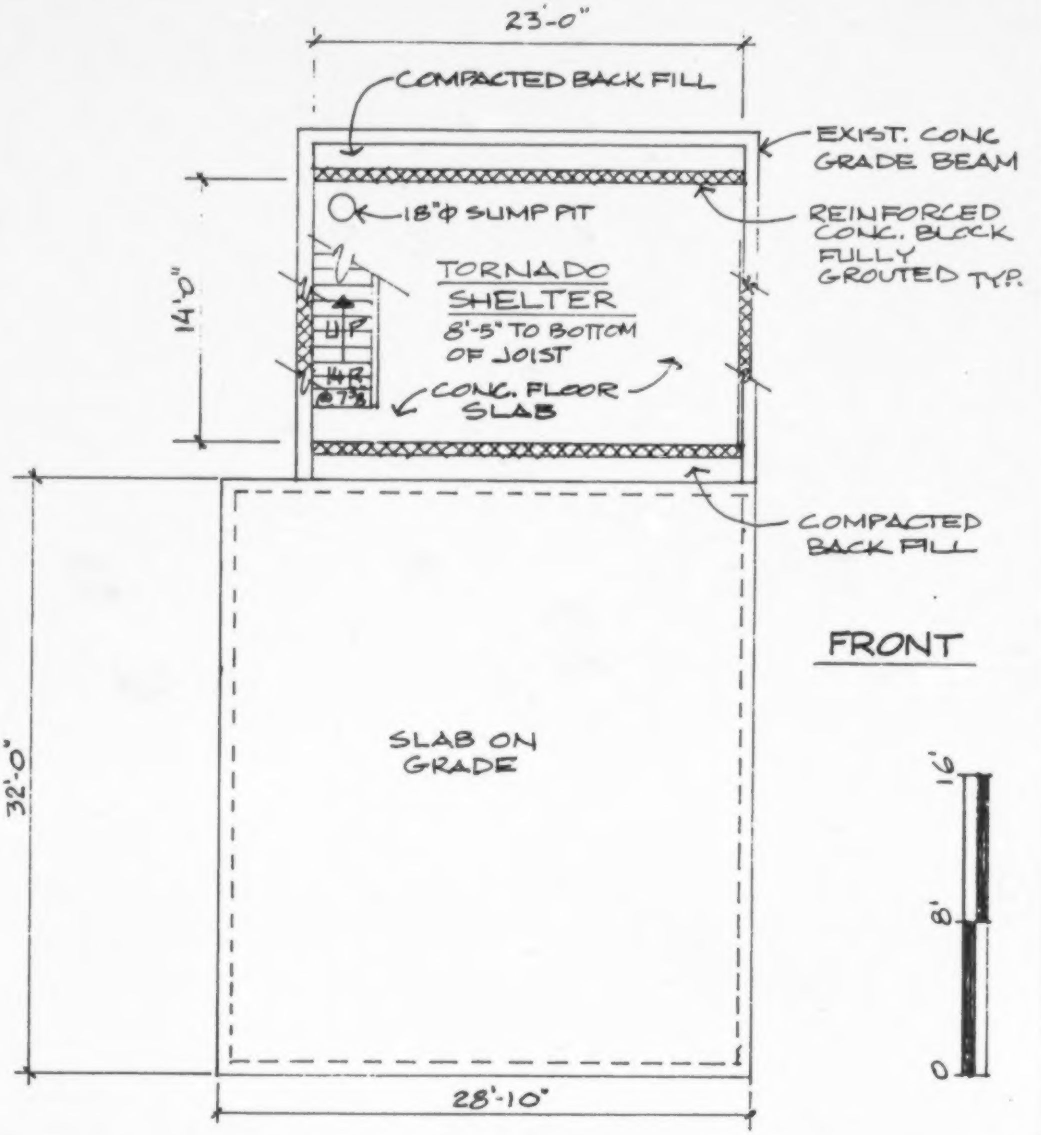
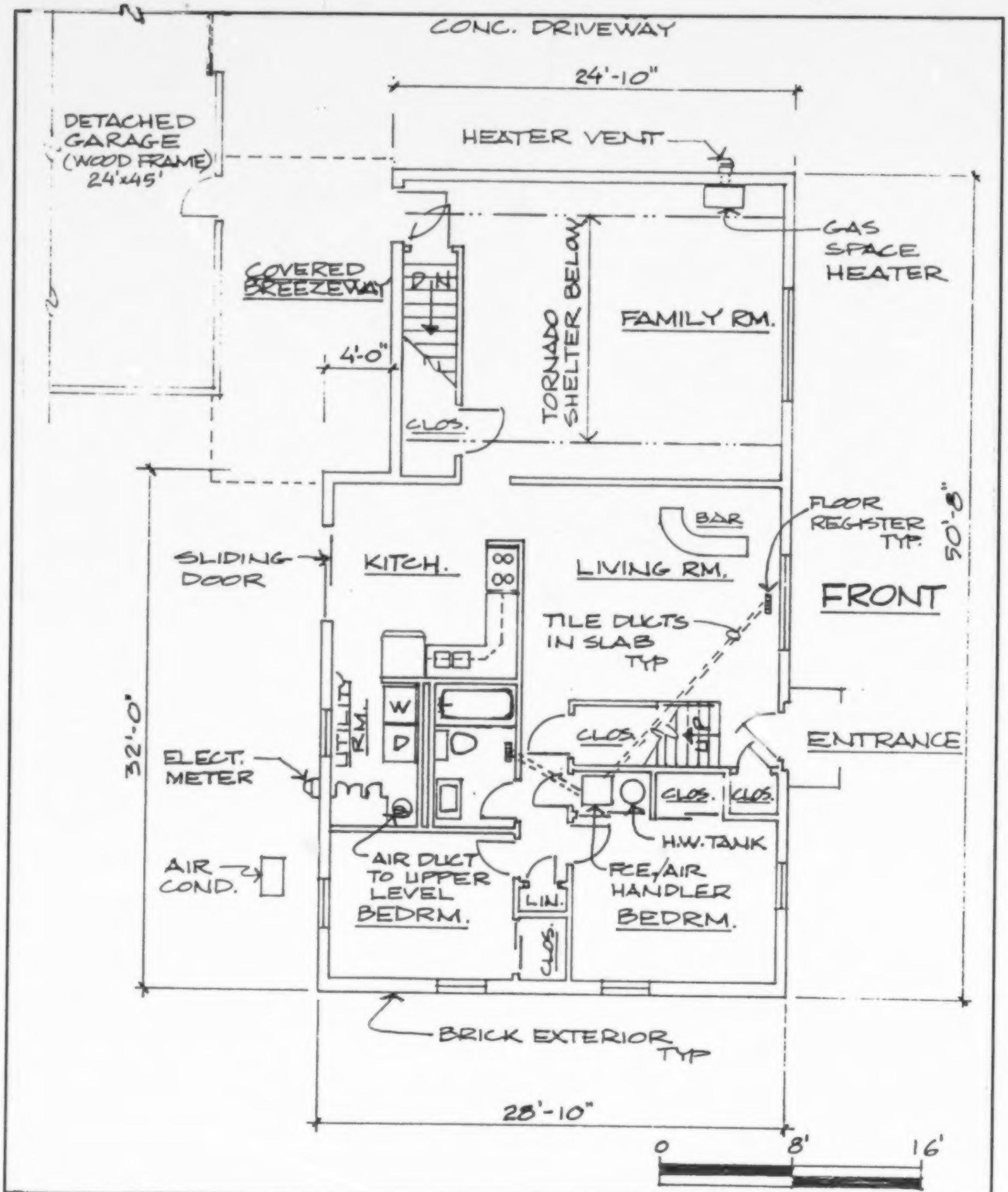


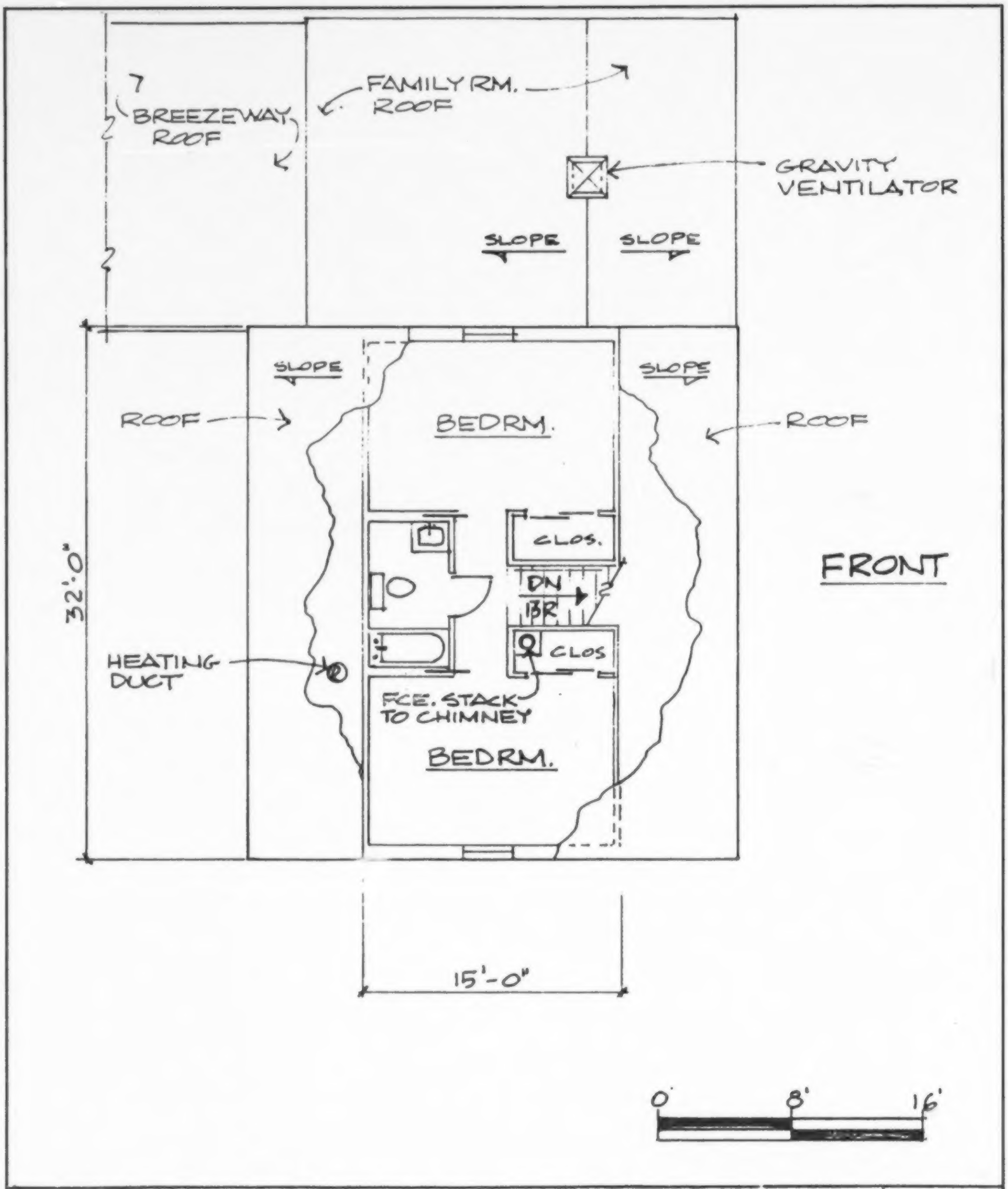
Figure 21-10. Sub-slab suction in basement, permanent installation (basement measurement)



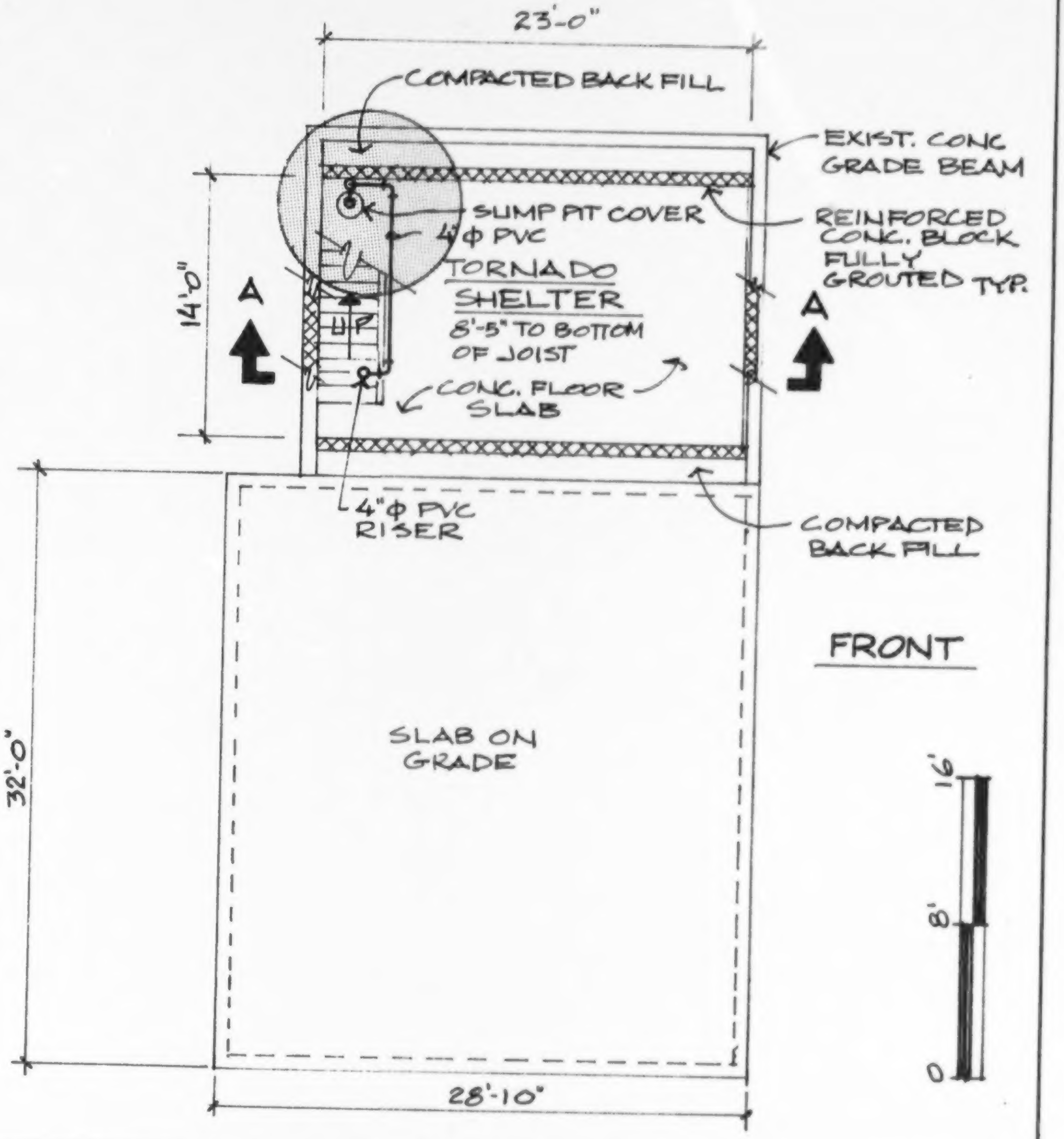
ACRES	LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
	BASEMENT/FOUNDATION PLAN	Date: 2/22/88	21
	House Group: PARTIAL BASEMENT	PHASE:	



ACRES	LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
	GRADE LEVEL PLAN	Date: 2/22/88	21
	House Group: PARTIAL BASEMENT	PHASE:	



ACRES Acres International Corporation	LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
	SECOND LEVEL PLAN	Date: 2/22/88	21
	House Group: PARTIAL BASEMENT	PHASE:	



ACRES
Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON

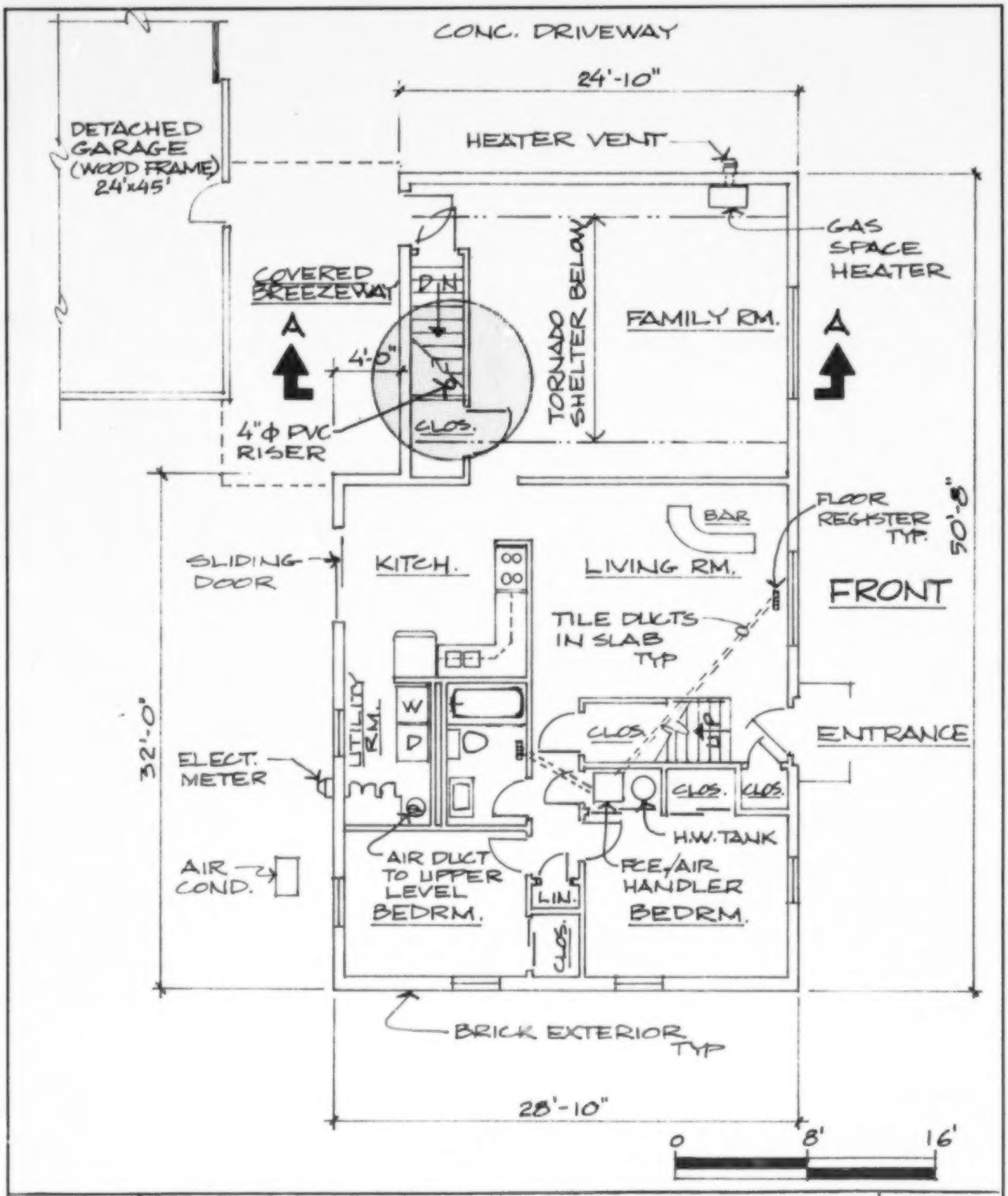
HOUSE NUMBER
21

BASEMENT/FOUNDATION PLAN

Date: MAY 1988

Mitigation system: SUMP SUCTION

PHASE: TEST AND FINAL



Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON

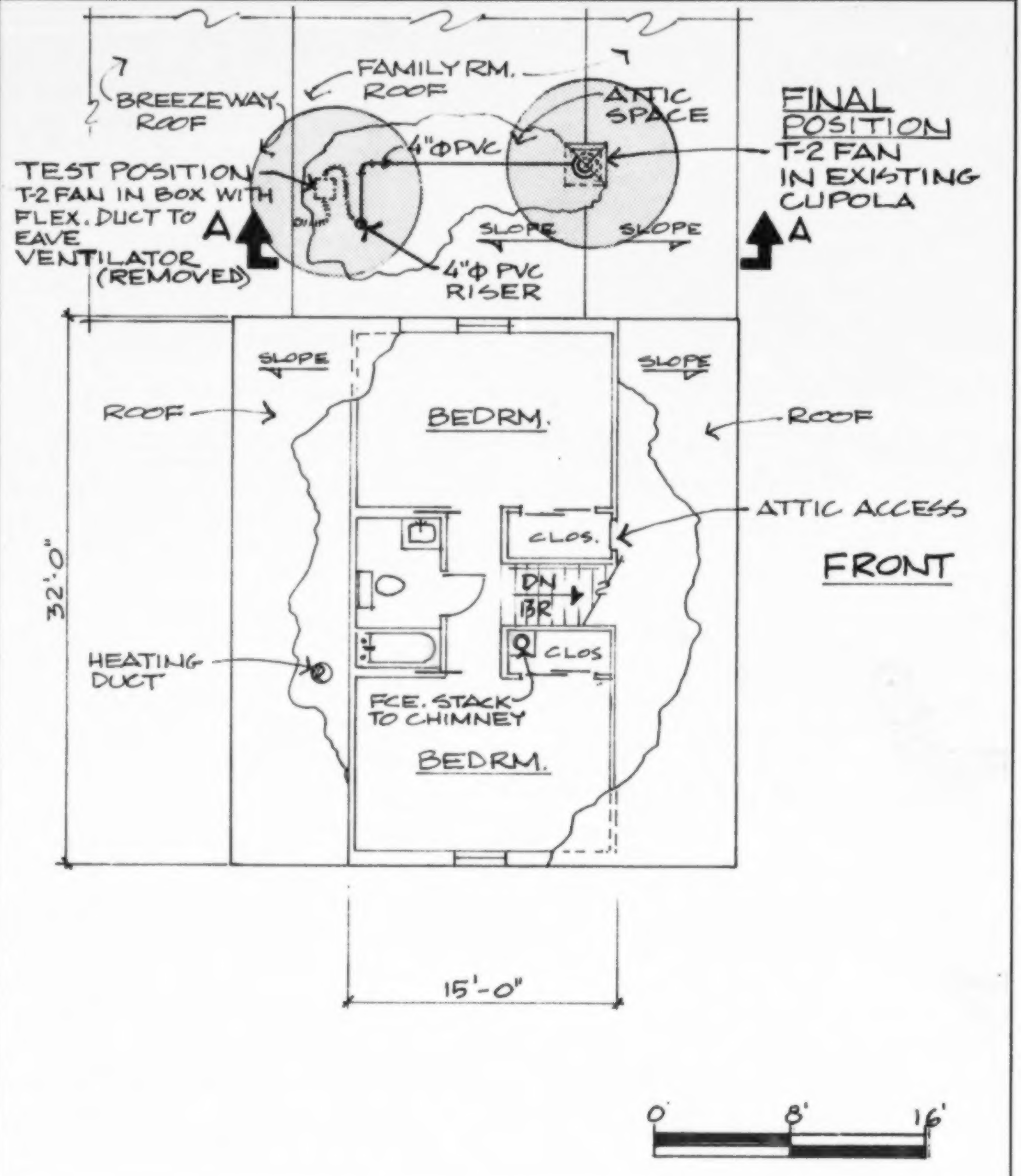
HOUSE NUMBER 21

GRADE LEVEL PLAN

Date: MAY 1988

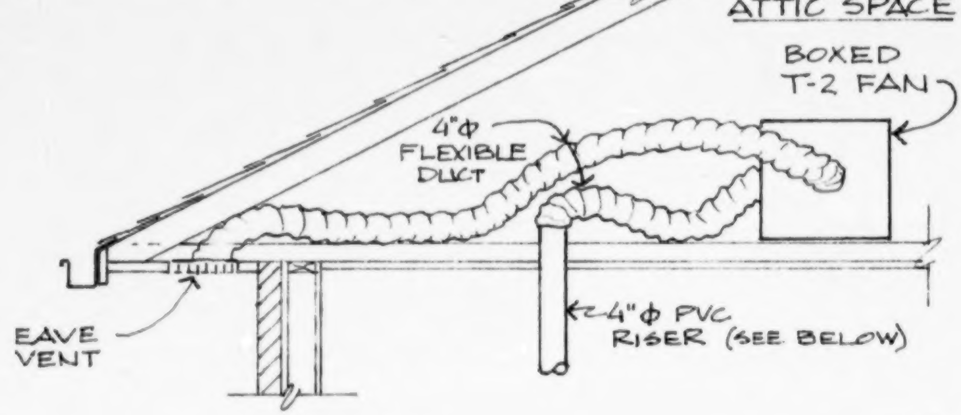
Mitigation system: SUMP SUCTION

PHASE: TEST AND FINAL

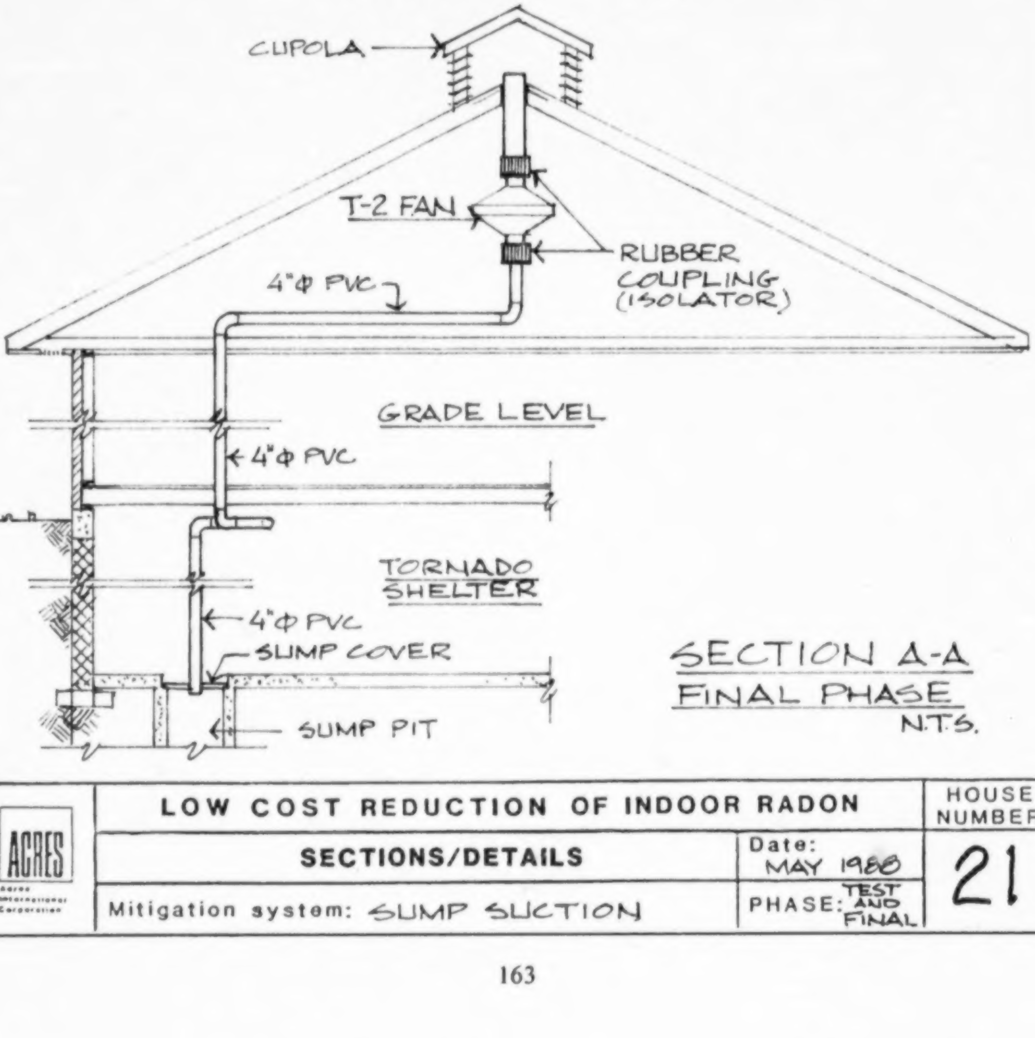


ACRES
Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
SECOND LEVEL PLAN	Date: MAY 1988	21
Mitigation system: SUMP SUCTION	PHASE: TEST AND FINAL	



DETAIL
TEST PHASE N.T.S.



SECTION A-A
FINAL PHASE
N.T.S.

ACRES International Corporation	**LOW COST REDUCTION OF INDOOR RADON**	HOUSE NUMBER
	SECTIONS/DETAILS — Date: MAY 1988	21
	Mitigation system: SUMP SUCTION — PHASE: TEST AND FINAL	

HOUSE 22

1 GENERAL DESCRIPTION

This large (240 m^2) single-story crawl-space house with attached garage was built in the mid 1980's in a rural setting north of Troy. The foundation walls are of hollow concrete block and the exterior walls are brick. Entry to the crawl space is by a trap door in a bedroom closet to a 2.5 by 3.0 m concrete block tornado shelter, and then into the crawl space via an opening in the shelter wall. There is also an entry into the shelter from outside via a steel trap door in a window-well. There are 8 vents in the crawl-space foundation wall, with 20 by 40 cm hit-and-miss ventilator grilles; there are custom-fitted wooden panels to close the vents in winter. The crawl-space floor is gravel on top of the native soil, with the gravel generally covered with plastic sheeting. There is a perforated plastic drain-pipe around the perimeter of the crawl space adjacent to the footing. There is no insulation between the joists supporting the wooden floor, but the crawl-space walls are covered with foam-board insulation.

The house floor is covered with wall-to-wall carpeting except for the vestibule which has a covering of vinyl plastic. Water is obtained from a well; the pressure tank is in the crawl space. Heating is by an electric forced-air furnace with metal supply and return ducts in the crawl space. Connections between the crawl space and the living area include the heating duct network, and openings in the floor for the sewer and water pipes.

2 INVESTIGATION

In January 1988, a short-term radon-monitor measurement made as part of the pre-selection process found radon concentrations in the crawl space with the vents closed ranging from 28 to 39 pCi/L, averaging 33.5 pCi/L, over 21 hours, and concentrations in the living area ranging from 19 to 32 pCi/L, averaging 24.8 pCi/L over 29 hours.

In April 1988, further radon monitoring was conducted with the crawl-space vents closed (considered the "pre-mitigation" condition). Over an 89-hour period, levels in the crawl space ranged from 17 to 38 pCi/L, averaging 25.8 pCi/L (Figure 22-4), while concentrations in the living room ranged from 7 to 24 pCi/L, averaging 14.4 pCi/L (Figure 22-3). Radon levels in the living room showed a diurnal pattern which was not evident in the crawl-space results, suggesting that there were daily variations in the transfer rate of crawl-space air to the living area. There is a fireplace with glass doors in the living room, and the occupants light a fire during the day. This could induce increased airflows out of the crawl space to supply the excess air.

Perfluorocarbon tracer (PFT) studies were also carried out at the same time to measure ventilation and transfer rates. The two measurements of the living space ventilation rate gave 0.27 and 0.32 ac/h, and for the crawl space were 0.21 and 0.29 ac/h. Although these are reasonable results, the ratios of living-area concentration to crawl-space concentration for a tracer released in the crawl space (0.09 and 0.23) were much lower than the ratio of average radon concentrations (0.54). This may be due to poor mixing of the tracer in the crawl space leading to unrepresentatively high concentrations at the nearby collector.

A temporary fan was connected to a wood panel placed in the exterior crawl-space entrance, to exhaust the crawl space at 57 L/s. Radon concentrations in the crawl space ranged from 17 to 33 pCi/L, averaging 24 pCi/L over a 117-hour period (from Figures 22-5 and 22-7), while levels in the living area ranged from 0 to 11 pCi/L, averaging 4.4 pCi/L over a 113-hour period (Figures 22-6 and 22-8). The lowest living-area concentrations occurred with crawl-space concentrations approaching pre-mitigation levels.

PFT studies conducted under these conditions indicated little change in the living area ventilation rate at 0.36 ac/h, compared with 0.32 ac/h without the fan, but the indicated crawl-space ventilation rate increased from 0.21 to 0.53 ac/h. However, this is equivalent to 103 m^3/h, which is only half the nominal forced exhaust rate of 205 m^3/h. The living-area to crawl-space concentration ratio of 0.07 for a tracer released in the crawl space is about half of the radon ratio of 0.16.

When the foundation vents were opened to provide natural crawl-space ventilation and the exhaust fan turned off, radon levels in the crawl space ranged from 4 to 16 pCi/L, averaging 10.7 pCi/L (Figure 22-8), while upstairs levels ranged from 4 to 14 pCi/L, averaging 9.1 pCi/L (Figure 22-7), over a 52-hour period. Thus, although compared to the "vents closed" case the crawl-space radon was reduced by almost two thirds, living space radon was reduced by little more than one third, and radon concentrations in both areas were close to identical, suggesting that almost all the air that entered the living area came from the crawl space. Simultaneous PFT measurements indicated that the ventilation rates were virtually unchanged at 0.55 ac/h for the crawl space, and 0.34 ac/h for the living area. However, the concentration ratio for the crawl space tracer was 0.10, which is so much lower than the measured radon ratio of 0.9 that it suggests the PFT tracer was not entering the house by the same route as the radon.

In mid-April 1988, a permanent crawl-space ventilation system consisting of a T-2 fan mounted on a plywood panel was installed inside the crawl space, exhausting through a foundation vent opening at the rear of the house.

In late May 1988, a hand-held auger was used to drill a hole at a site between the rear deck and the air-conditioning compressor, clear of all underground lines. The auger penetrated to a depth of approximately 165 cm through clay before refusing to penetrate deeper.

3 OTHER MEASUREMENTS

The 1987 charcoal canister test found an average radon concentration of 22.5 pCi/L in the crawl space. A short-term radon-monitor survey in January 1988 found concentrations in the crawl space ranged from 28 to 39 pCi/L, averaging 33.5 pCi/L, while concentrations in the living room ranged from 19 to 32 pCi/L, averaging 24.8 pCi/L.

Pre-mitigation alpha-track measurements with the crawl-space vents closed over the period December 1987 to February 1988 gave average radon concentrations of 15.0 pCi/L in the living area and 25.6 pCi/L in the crawl space.

Alpha-track measurements with the crawl-space vents open over the period May to August 1988 gave average radon concentrations of 3.9 pCi/L in the living area, and 8.0 pCi/L in the crawl space.

The gamma radiation field in the house ranged from 4 to 6 μR/h, averaging 5 μR/h, whereas the gamma field on the site averaged 6 uR/h, with fields from 9 to 11 μR/h from the house bricks.

MEASUREMENTS SUMMARY FOR HOUSE 22

PYLON AB-5 HOURLY MONITORING

MITIGATION SYSTEM	TEST DATE	TEST STATUS	RADON(pCi/L) RANGE	MEAN	DURATION/ LOCATION	FIG.
pre-selection	01/88		28-39	33.5	21 hrs; CS*	22-1
			19-32	24.8	29 hrs; LR*	22-2
pre-mitigation	04/88	vents closed	17-38	25.8	89 hrs; CS	22-4
		vents closed	7-23	14.4	89 hrs; LR	22-3
crawl-space exhaust	04/88	fan on max.	17-33	23.4	91 hrs; CS	22-6
		fan on max. (vents closed)	0-10	3.7	91 hrs; LR	22-5
	04/88	fan on max.	22-32	25.7	21 hrs; CS	22-8
		fan on max. (vents closed)	7-11	7.6	21 hrs; LR	22-7
natural crawl-space ventilation	04/88	vents open	5-15	10.7	47 hrs; CS	22-8
		vents open	5-14	9.1	47 hrs; LR	22-7

* CS=Crawl Space; LR=Living Room

Average pre-mitigation Pylon results (presented in Tables XII, XIII and 3):

Living area
Weighted average of Figures 22-2 and 22-3 (118 hours total) = 17.0 pCi/L.

Crawl space
Weighted average of Figures 22-1 and 22-4 (110 hours total) = 27.3 pCi/L.

Average post-mitigation Pylon results:

Living area
natural crawl-space vent (Table XII) — natural vent portion of Fig. 22-7 (47 hr) = 9.1 pCi/L.
forced crawl-space exhaust (Table XIII) — Fig. 22-5 and force exhaust portion of 22-7 (112 hours total) = 4.4 pCi/L

Crawl space
natural crawl-space vent — natural vent portion of Fig. 22-8 (47 hr) = 10.7 pCi/L.
forced crawl-space exhaust — Fig. 22-6 and forced-exhaust portion of 22-8 (112 hours total) = 23.8 pCi/L.

SYSTEMS MEASUREMENTS

PHASE	MITIGATION SYSTEM	TEST DATE	MEASUREMENTS SUCTION (Pa)	 FLOW (L/s)	 RADON (pCi/L)	COMMENT
1	crawl-space exhaust (fan on max.)	04/88		57		at fan

PFT VENTILATION STUDIES

TEST DATE	CRAWL-SPACE CONDITIONS	VENTILATION RATES LIVING AREA (m^3/h)	 (ac/h)	 CRAWL SPACE (m^3/h)	 (ac/h)	CONCENTRATION RATIO (LIVING/CRAWL)
3-4/88	vents closed	146	0.27	56	0.29	4.9/21.1
4/88	vents closed	171	0.32	41	0.21	2.7/30.9
4/88	" + exhaust on	196	0.36	103	0.53	0.9/12.3
4/88	vents open	184	0.34	106	0.55	1.2/11.8

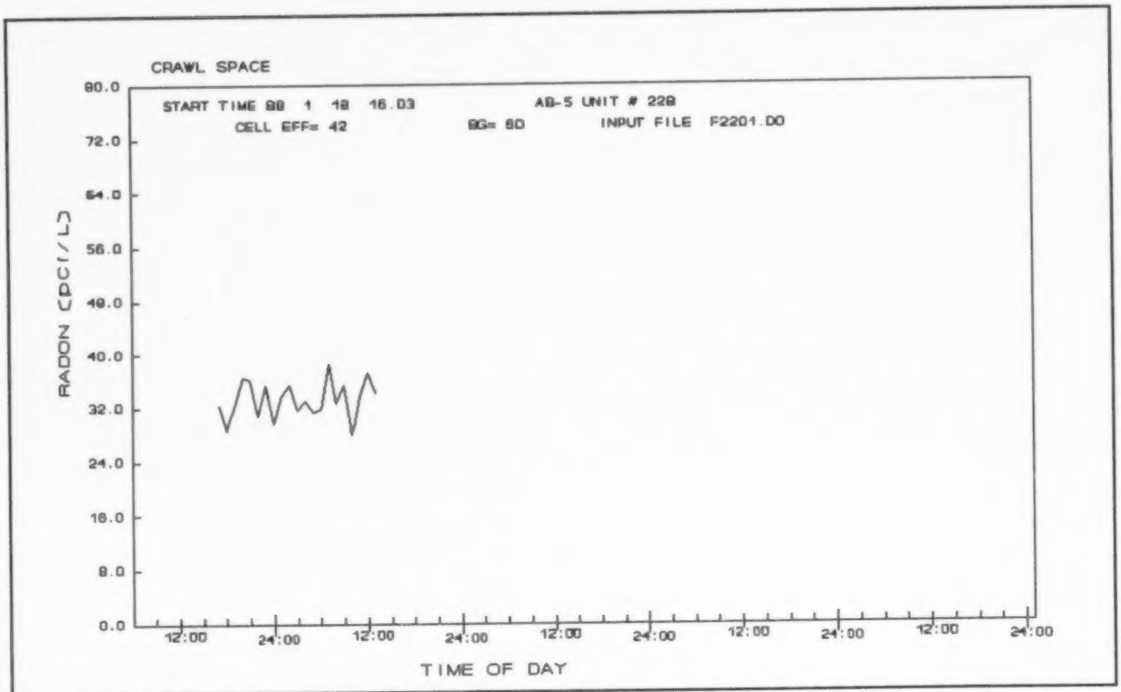


Figure 22-1. Pre-selection monitoring (crawl space)

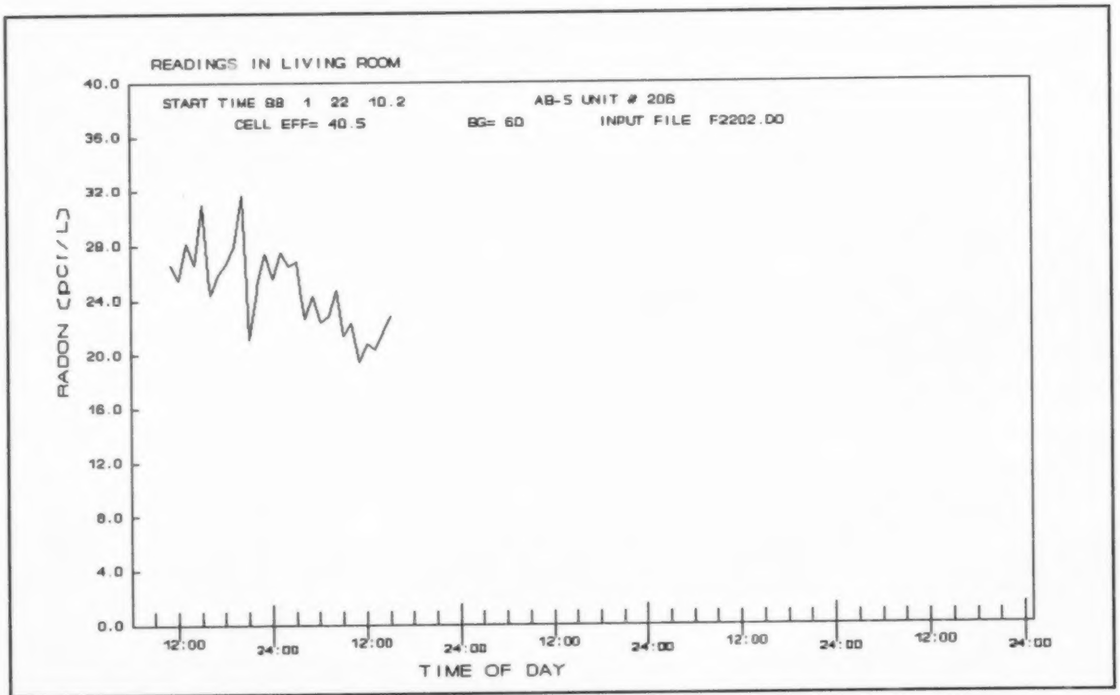


Figure 22-2. Pre-selection monitoring (living area)

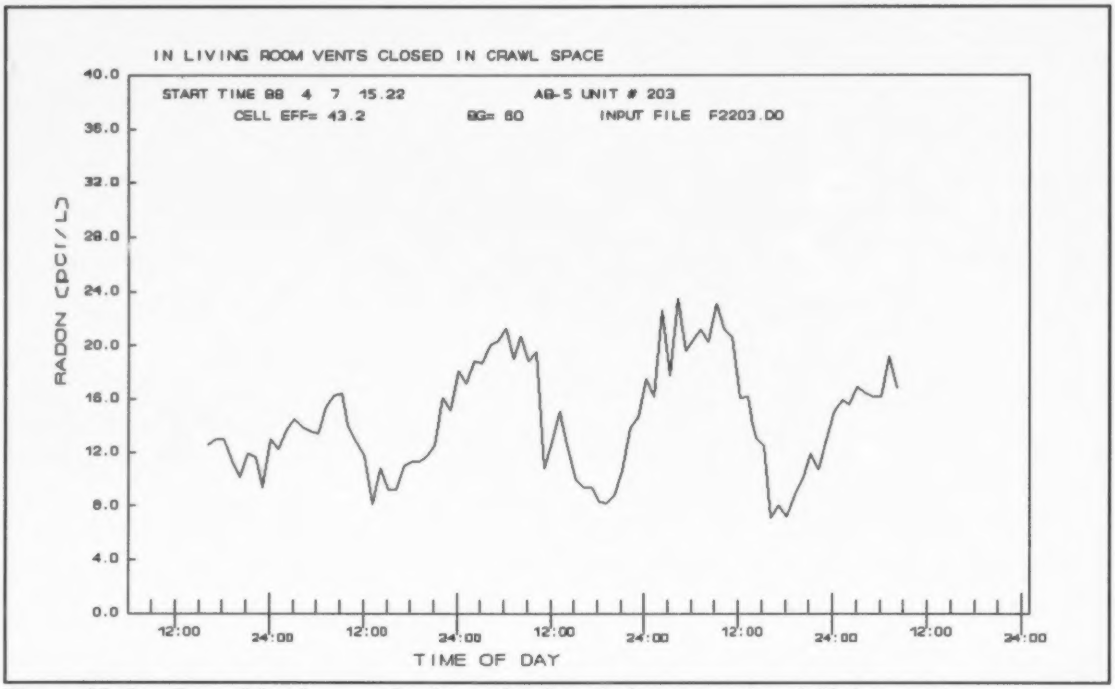


Figure 22-3. Pre-mitigation monitoring, with foundation vents closed (living area)

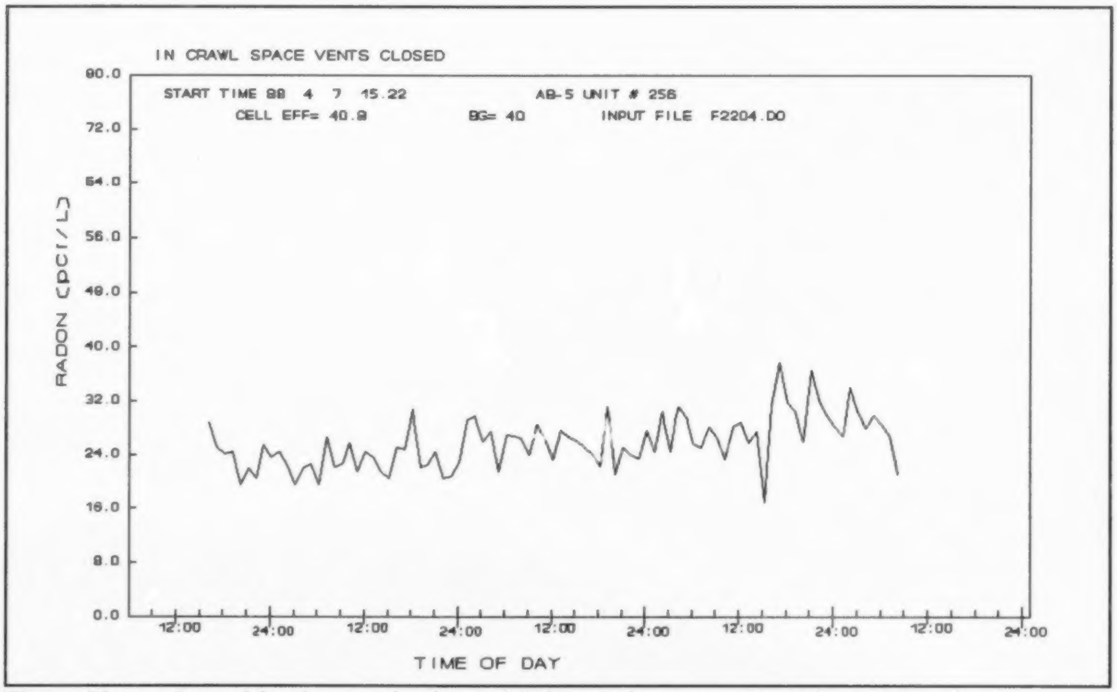


Figure 22-4. Pre-mitigation monitoring, with foundation vents closed (crawl space)

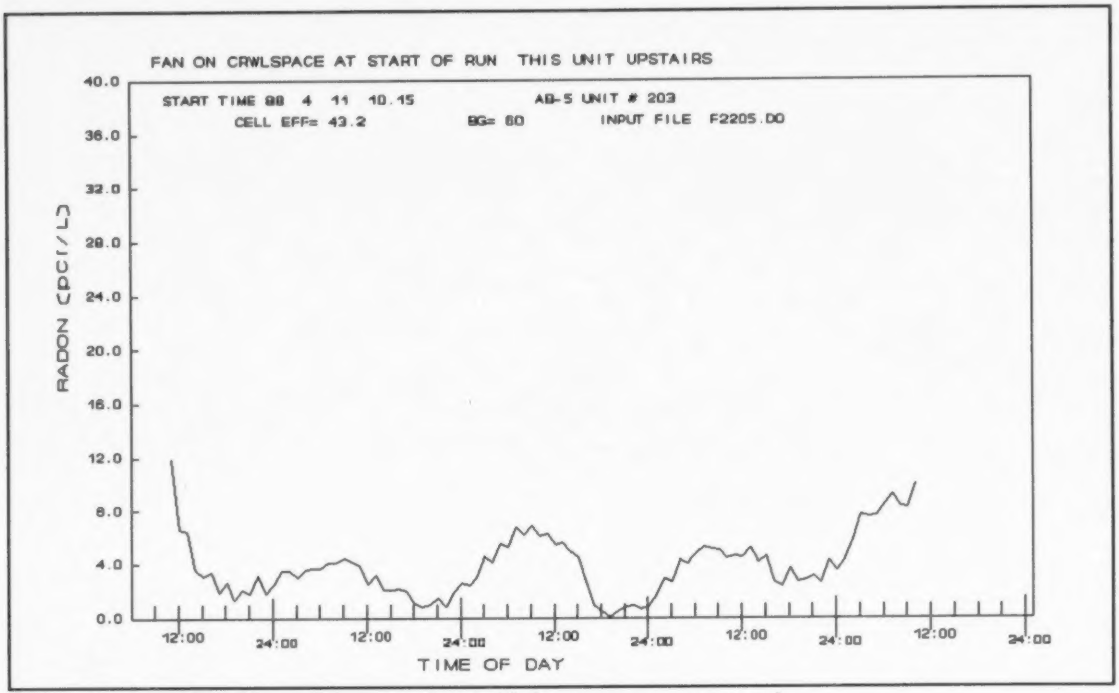


Figure 22-5. Forced crawl-space exhaust (living area measurement)

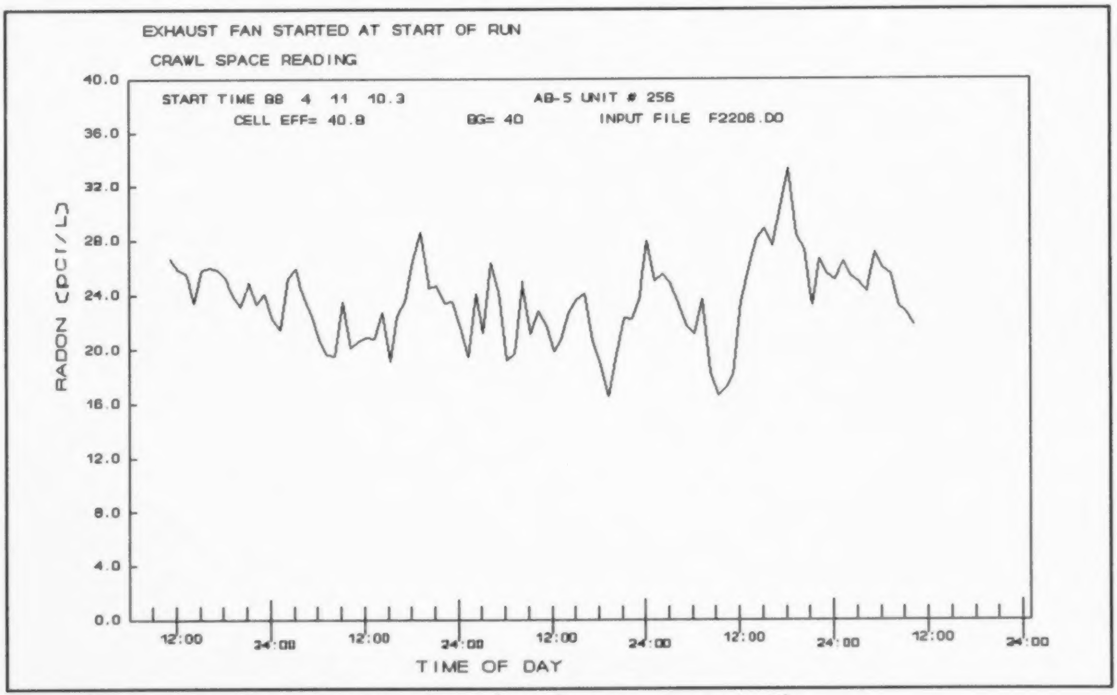


Figure 22-6. Forced crawl-space exhaust (crawl space measurement)

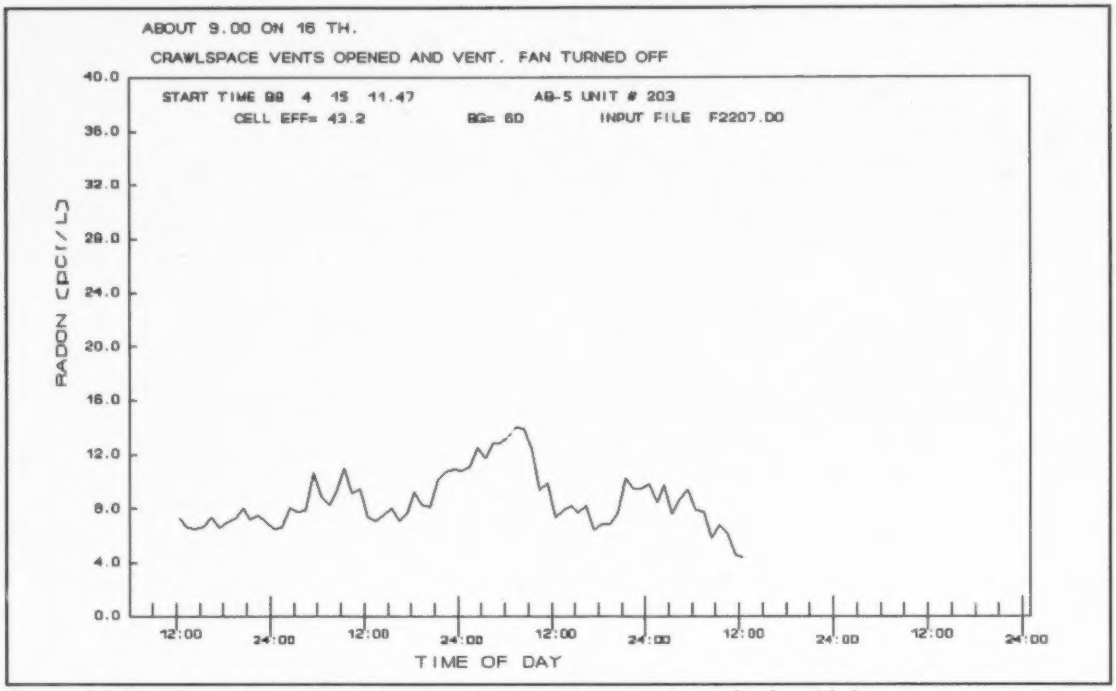


Figure 22-7. Forced crawl-space exhaust vs. natural crawl ventilation (living area measurement)

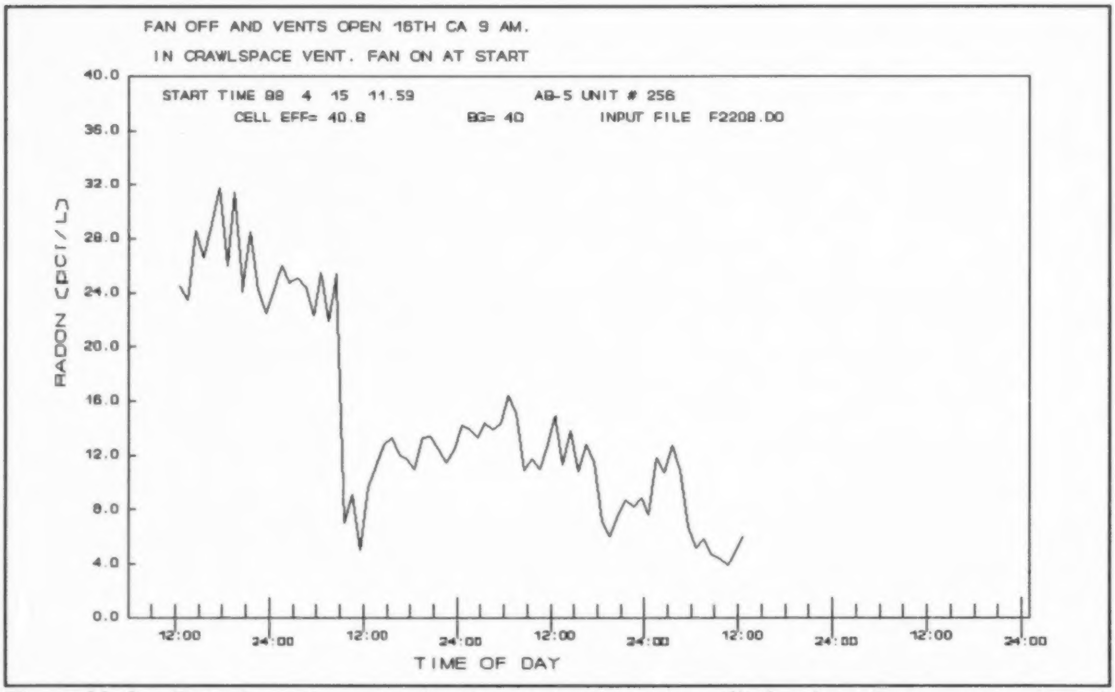
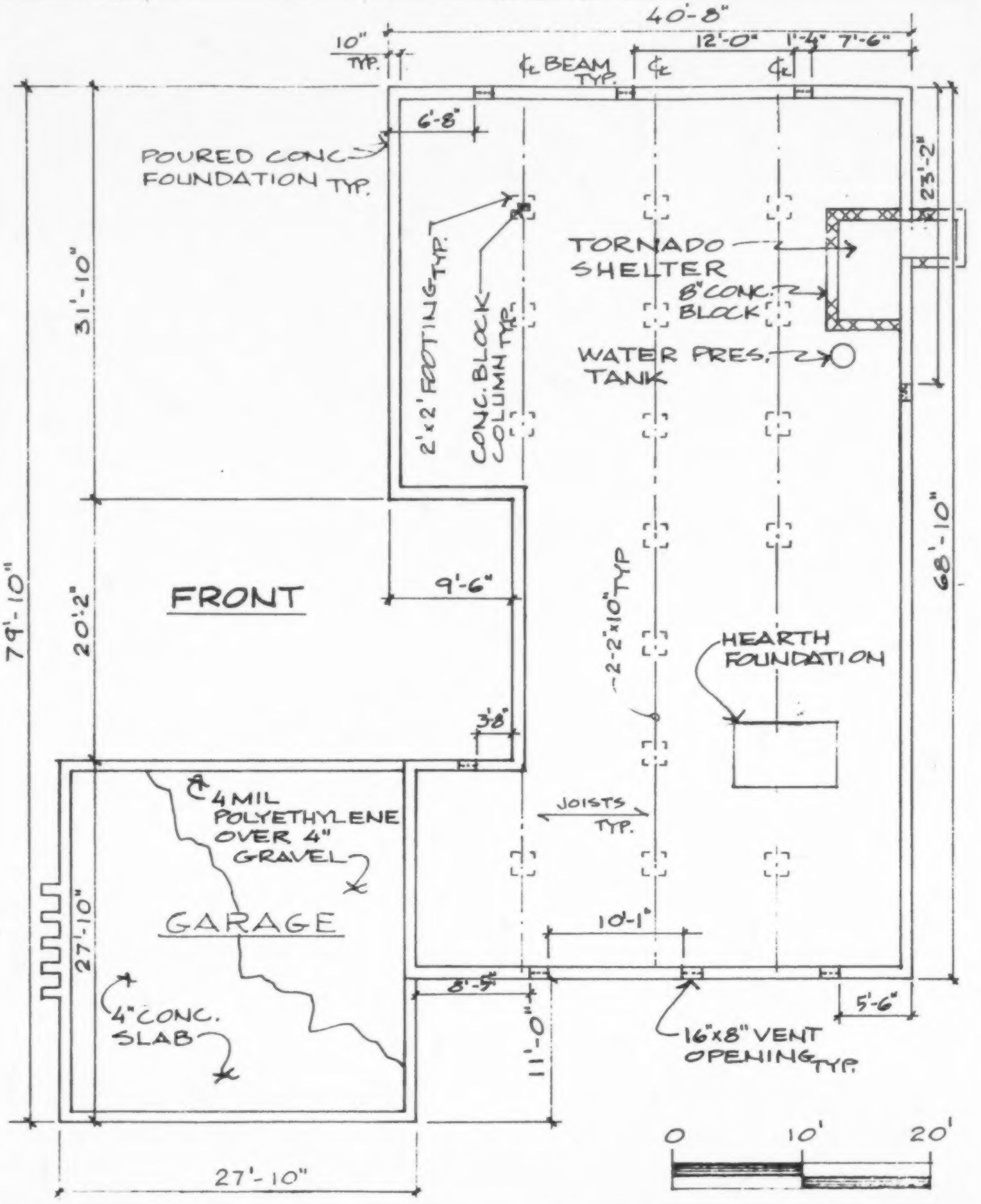
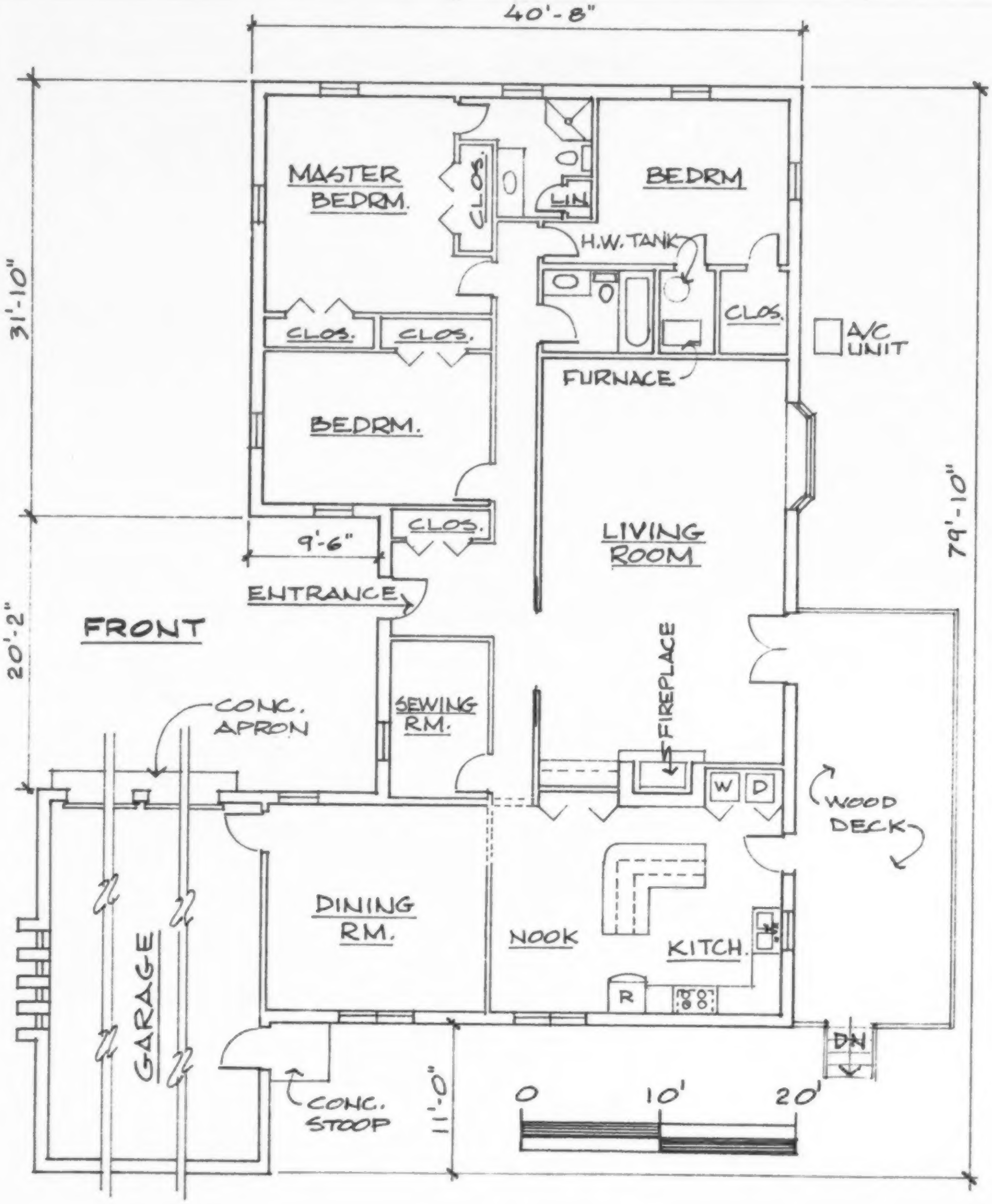


Figure 22-8. Forced crawl-space exhaust vs. natural crawl ventilation (crawl space measurement)



ACRES Acres International Corporation	LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
	CRAWL SPACE	Date: MAY 1988	22
	House Group: CRAWL SPACE	PHASE:	



ACRES
Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON

HOUSE NUMBER

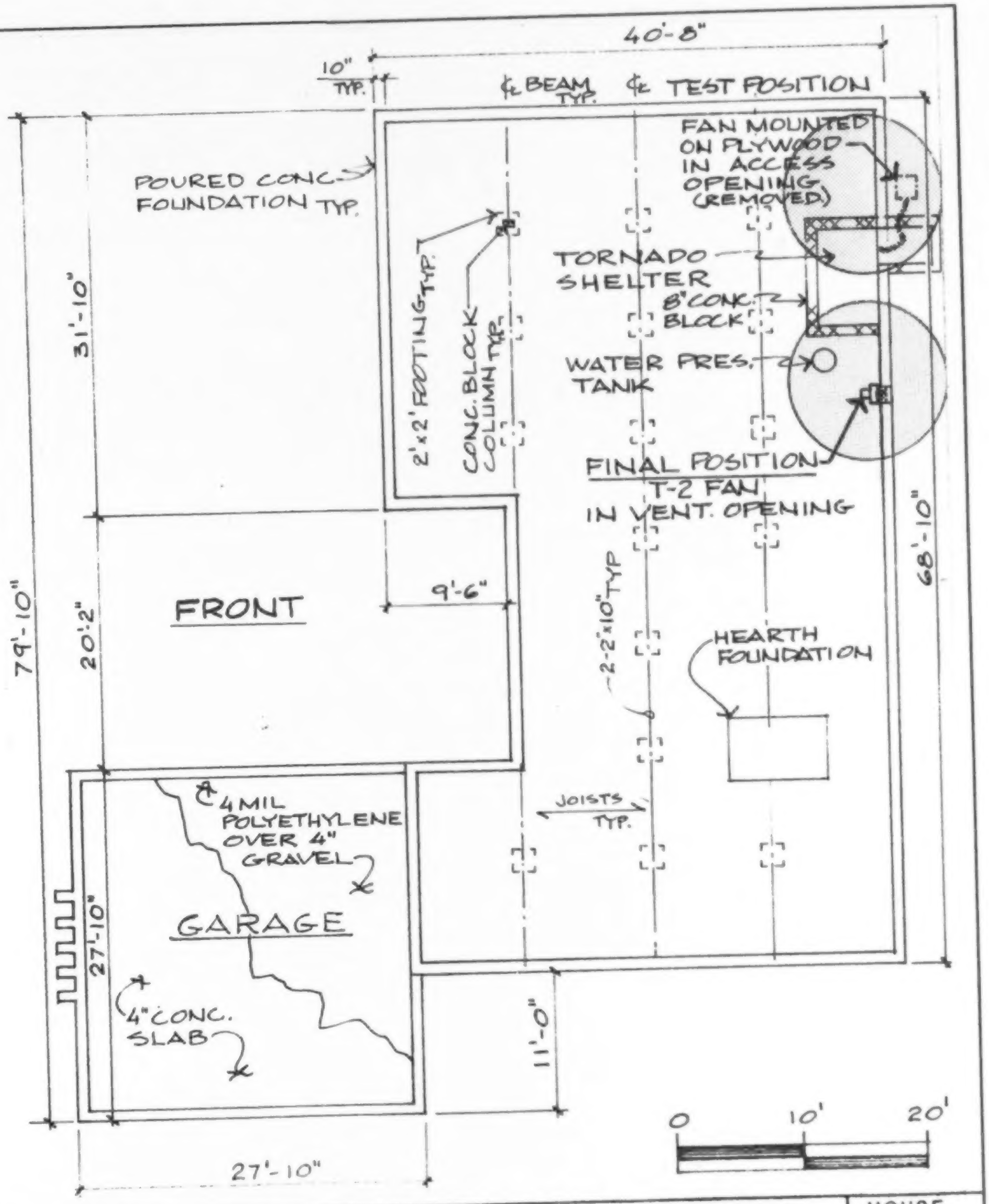
GRADE LEVEL PLAN

Date: 3/26/88

22

House Group: **CRAWL SPACE**

PHASE:



ACRES
Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON

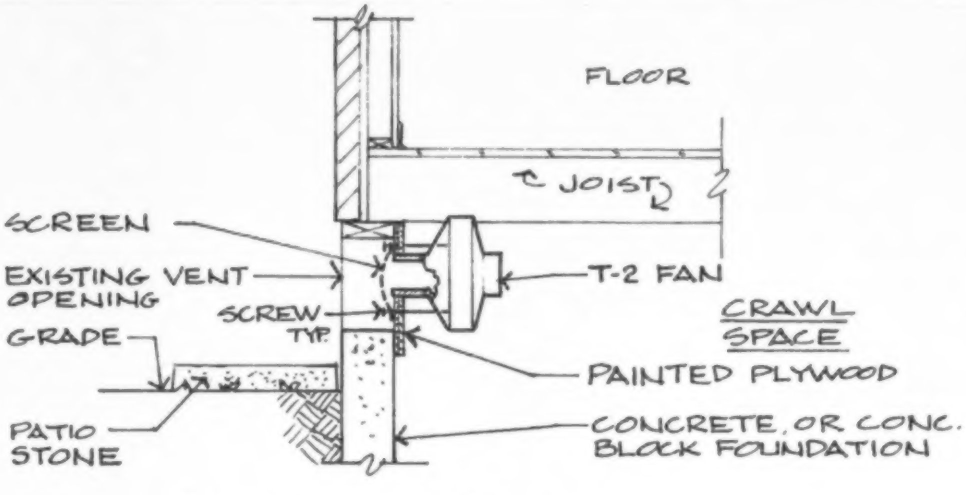
HOUSE NUMBER
22

CRAWL SPACE

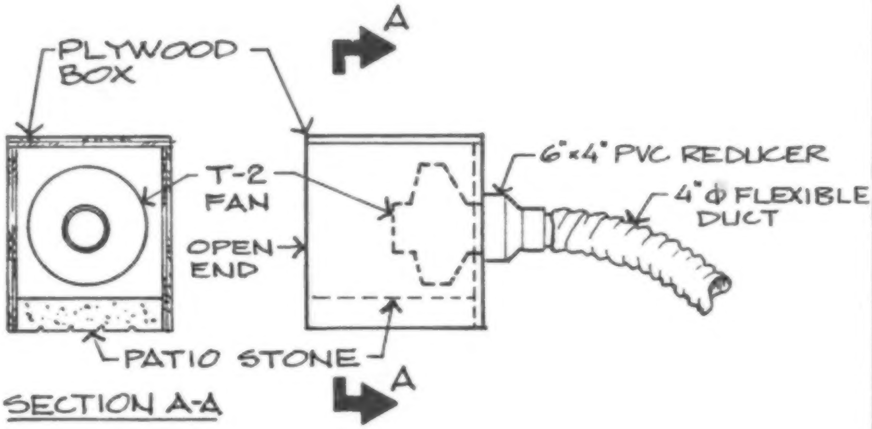
Date: MAY 1988

Mitigation system: CRAWL SPACE VENTILATION

PHASE: TEST AND FINAL



FINAL SYSTEM
N.T.S.



TEST SYSTEM
N.T.S.

ACRES Acres International Corporation	LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
	SECTIONS/DETAILS	Date: MAY 1988	22
	Mitigation system: CRAWL SPACE VENTILATION	PHASE: TEST AND FINAL	

HOUSE 24

1 GENERAL DESCRIPTION

This small (120 m^2) single-story crawl-space house with attached was built in the early 1970's in a rural setting north of Troy. The foundation walls are of hollow concrete block and the exterior walls are of brick. Entry to the crawl space is by a trap door in the garage. The crawl space has an air conditioning unit in the center, with radial duct-work and the floor is covered with plastic sheet placed over crushed stone of less than 5 mm diameter. There are 3 air vents 40 by 20 cm through the crawl-space foundation wall above ground, closed by internal flaps in winter. There is paper-backed Fiberglass bat insulation between the joists supporting the overhead wooden floor. This floor is mainly covered with wall-to-wall carpeting but the kitchen has a covering of vinyl plastic. Water is obtained from a well, with the pressure tank located in the crawl space. Heating is by electrical baseboard convectors. Connections between the crawl space and the living area include the air conditioning duct network, and openings around the sewer and water pipes.

2 INVESTIGATION

In January 1988, a short-term continuous radon monitor measurement made as part of the preselection process found that over 22 hours concentrations in the crawl space ranged from 22 to 36 pCi/L, averaging 27.6 pCi/L, while concentrations in the living room ranged from 6 to 19 pCi/L, averaging 13.6 pCi/L over 40 hours.

In April 1988, further radon monitoring was conducted with the crawl-space vents closed (considered the "pre-mitigation" condition). Over a 65-hour period, levels in the crawl space ranged from 23 to 40 pCi/L, averaging 34.1 pCi/L (Figure 24-4), while concentrations in the living room ranged from 10 to 28 pCi/L, averaging 17.4 pCi/L (Figure 24-3).

Perfluorocarbon tracer (PFT) studies were also conducted at the same time to measure ventilation and inter-floor transfer rates. The ventilation rate for the living space was 0.17 ac/h while that for the crawl space was 0.24 ac/h. The ratio of living-area to crawl-space average concentration for the tracer released in the crawl space was 0.29 (11.5/40.1). This is a somewhat lower than the radon ratio of 0.50 (17/34), and may be the result of poor mixing of the tracer in the crawl space resulting in the detection of unrepresentatively high concentrations by the nearby collector.

When the vents were opened to provide natural crawl-space ventilation, radon levels in the crawl space ranged from 8 to 30 pCi/L, averaging 15.1 pCi/L, while upstairs levels ranged from 1 to 13 pCi/L, averaging 6.8 pCi/L, over a 93-hour period. Thus, the ratio of average radon concentrations in the living area to the crawl space was not changed, but the absolute values were reduced by roughly 60%.

When the vents were closed and a temporary fan installed to exhaust the crawl space at 47 L/s, radon concentrations in the crawl space ranged from 9 to 25 pCi/L, averaging 17.6 pCi/L, while concentrations in the living area ranged from 2 to 13 pCi/L, averaging 4.8 pCi/L, over an 85-hour period.

PFT studies conducted at the same time indicated little change in the living area ventilation rate. which was 0.19 ac/h with the fan on, compared with 0.17 ac/h without the fan. However, with the fan on the crawl-space ventilation rate was 0.35 ac/h, an increase from 0.24 ac/h without. However, this is less than the ventilation rate provided by the fan alone, and the tracer concentration ratio of 0.04 (1.1/27.5) is greatly different from the radon ratio of 0.27 (4.8/18).

In late May 1988, a permanent crawl-space ventilation system was installed. A plywood plate was fitted into a foundation vent opening, and a T-2 in-line centrifugal fan was installed on the plywood inside the crawl space, exhausting out through the vent. A fan-speed controller was mounted on the garage wall.

A test boring was carried out at that time with a hand-held auger. The auger was able to penetrate to a depth of 210 cm below site grade. The first 50 cm was of organic clay soil, the next 150 cm was hard damp clay.

3 OTHER MEASUREMENTS

The 1987 charcoal canister test gave a radon value of 51.4 pCi/L in the crawl space. A short-term radon-monitor survey in January 1988 found concentrations in the crawl space ranged from 22 to 36 pCi/L, averaging 27.6 pCi/L, while concentrations in the living room ranged from 6 to 19 pCi/L, averaging 13.6 pCi/L.

Pre-mitigation alpha-track measurements with the crawl-space vents closed over the period December 1987 to February 1988 gave average radon concentrations of 11.2 pCi/L in the living area and 21.1 pCi/L in the crawl space.

Alpha-track measurements made during the period May to August 1988, with the crawl-space vents open and with the exhaust fan off, gave average radon concentrations of 7.2 pCi/L in the living area, and 13.4 pCi/L in the crawl space.

The gamma radiation field in the house ranged from 5 to 6 μR/h, averaging 6 μR/h, whereas the gamma field over the site ranged from 5 to 10 μR/h, averaging 8 μR/h.

MEASUREMENTS SUMMARY FOR HOUSE 24

PYLON AB-5 HOURLY MONITORING

MITIGATION SYSTEM	TEST DATE	TEST STATUS	RADON(pCi/L) RANGE	MEAN	DURATION/ LOCATION	FIG.
pre-selection	01/88		22-36	27.6	22 hrs; CS*	24-1
			6-19	13.6	40 hrs; LR*	24-2
pre-mitigation	04/88	vents closed	23-40	34.1	65 hrs; CS	24-4
		vents closed	10-28	17.4	65 hrs; LR	24-3
crawl-space exhaust	04/88	fan on;DPmax	9-25	17.6	85 hrs; CS	24-6
		fan on;DPmax	2-13	4.8	85 hrs; LR	24-5
natural crawl-space ventilation	04/88	vents open	8-30	15.1	93 hrs; CS	24-8
		vents open	1-13	6.8	93 hrs; LR	24-7

* CS=Crawl Space; LR=Living Room

Average pre-mitigation Pylon results (presented in Tables XII, XIII and 3):

Living area
Weighted average of Figures 24-2 and 24-3 (105 hours total) = 15.9 pCi/L.

Crawl space
Weighted average of Figures 24-1 and 24-4 (87 hours total) = 32.5 pCi/L.

Average post-mitigation Pylon results:

Living area
natural crawl-space vent (Table XII) — Fig. 24-7 (93 hr) = 6.8 pCi/L.
forced crawl-space exhaust (Table XIII) — Fig. 24-5 (85 hr) = 4.8 pCi/L.

Crawl space
natural crawl-space vent (Table XII) — Fig. 24-8 (93 hr) = 15.1 pCi/L.
forced crawl-space exhaust (Table XIII) — Fig. 24-6 (85 hr) = 17.6 pCi/L.

SYSTEMS MEASUREMENTS

PHASE	MITIGATION SYSTEM	TEST DATE	MEASUREMENTS			COMMENT
			SUCTION (Pa)	FLOW (L/s)	RADON (pCi/L)	
1	crawl-space exhaust	04/88		47 (170 m^3/h)		at fan

PFT VENTILATION STUDIES

TEST DATE	CRAWL-SPACE CONDITIONS	VENTILATION RATES				CONCENTRATION RATIO (LIVING/CRAWL)
		LIVING AREA		CRAWL SPACE		
		(m^3/h)	(ac/h)	(m^3/h)	(ac/h)	
4/88	vents closed	47	0.17	31	0.24	11.5/40.1
4/88	exhaust on (170 m^3/h)	53	0.19	45	0.35	1.1/27.5

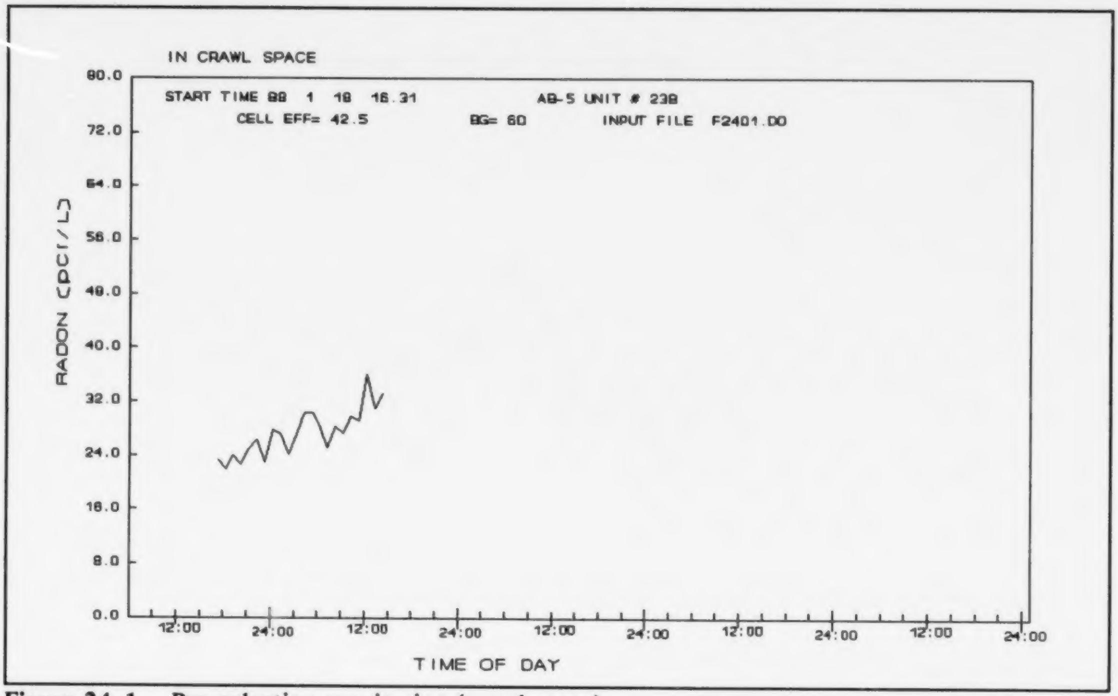


Figure 24-1. Pre-selection monitoring (crawl space)

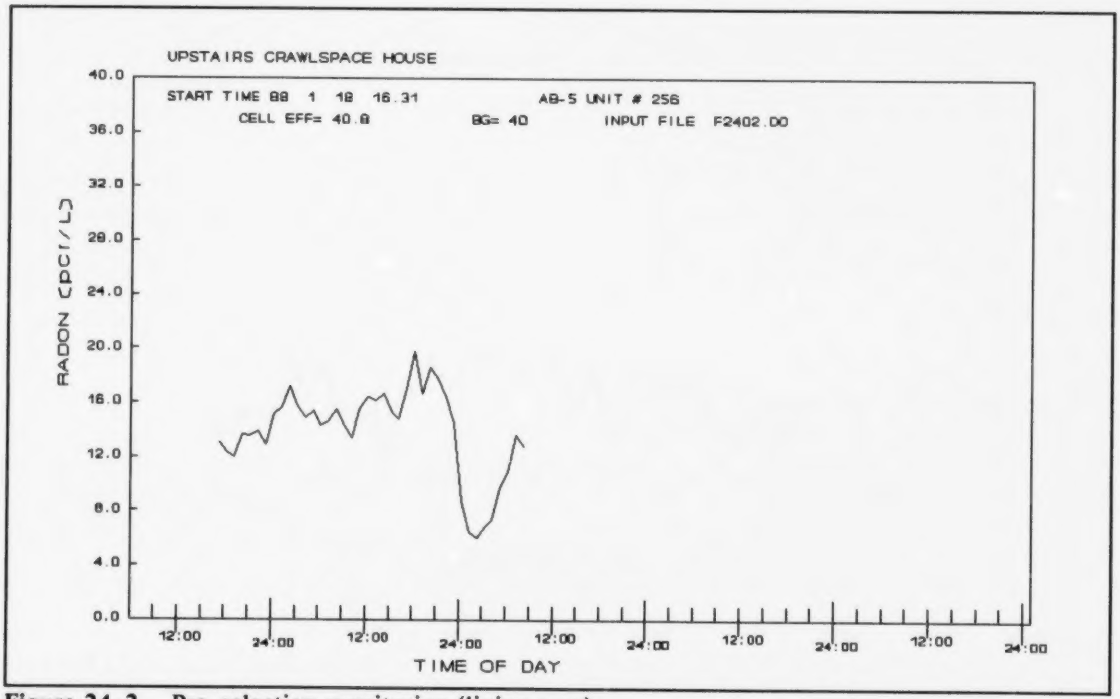


Figure 24-2. Pre-selection monitoring (living area)

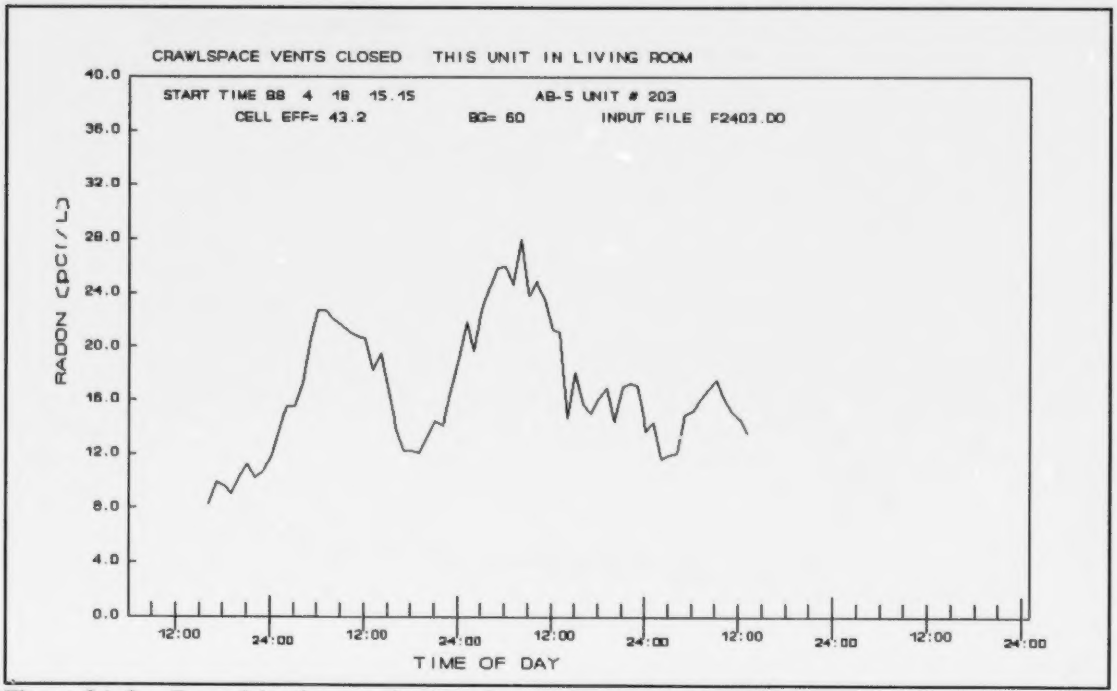


Figure 24-3. Pre-mitigation monitoring, foundation vents closed (living area)

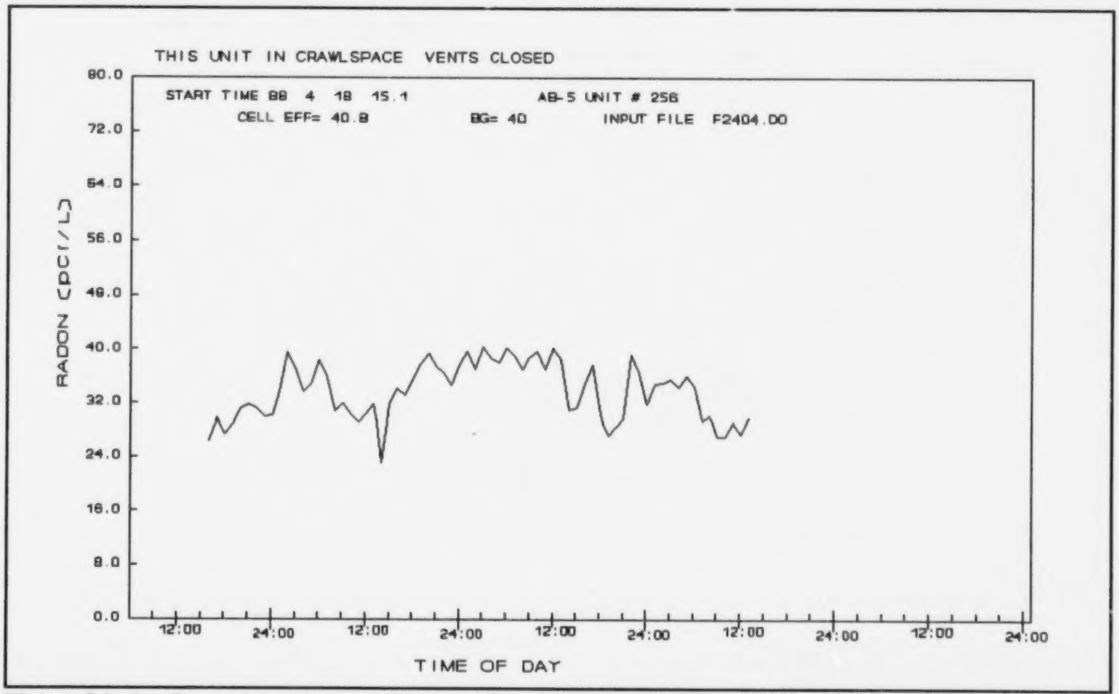


Figure 24-4. Pre-mitigation monitoring, foundation vents closed (crawl space)

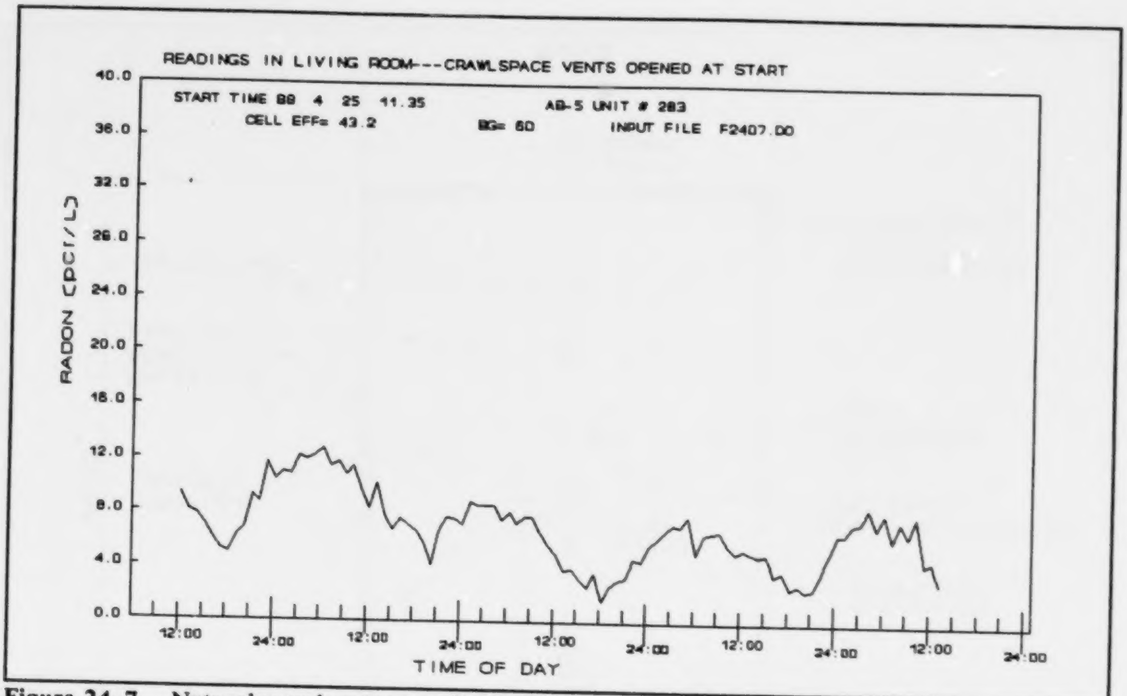


Figure 24-7. Natural crawl-space ventilation, foundation vents open (living area)

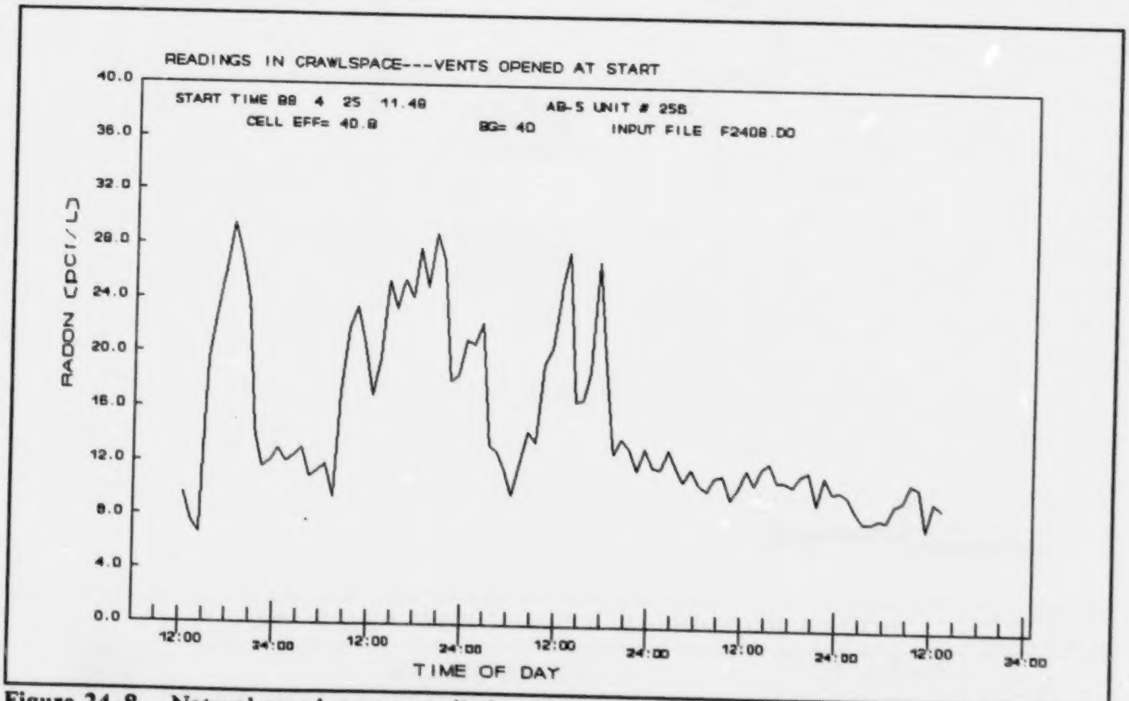
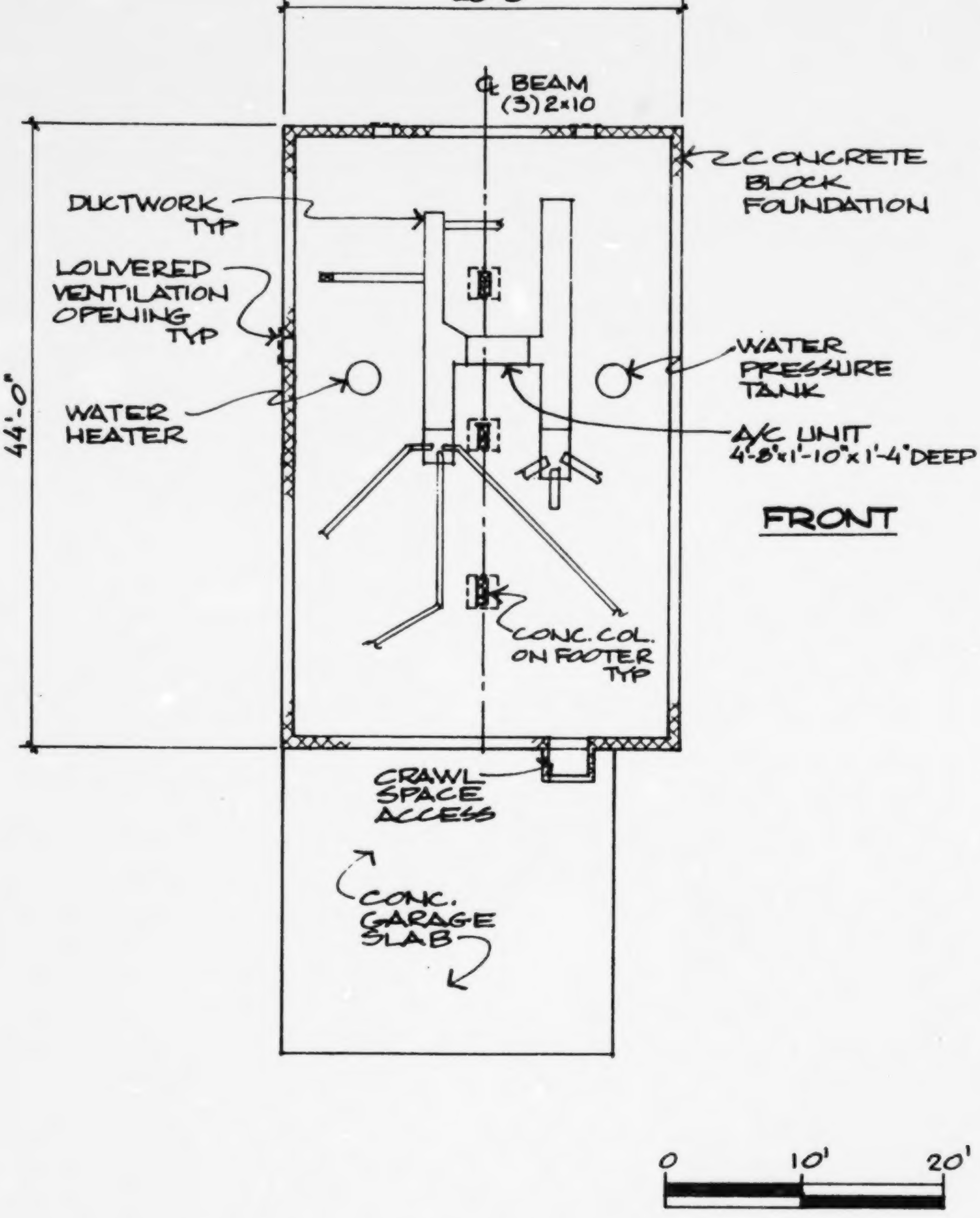
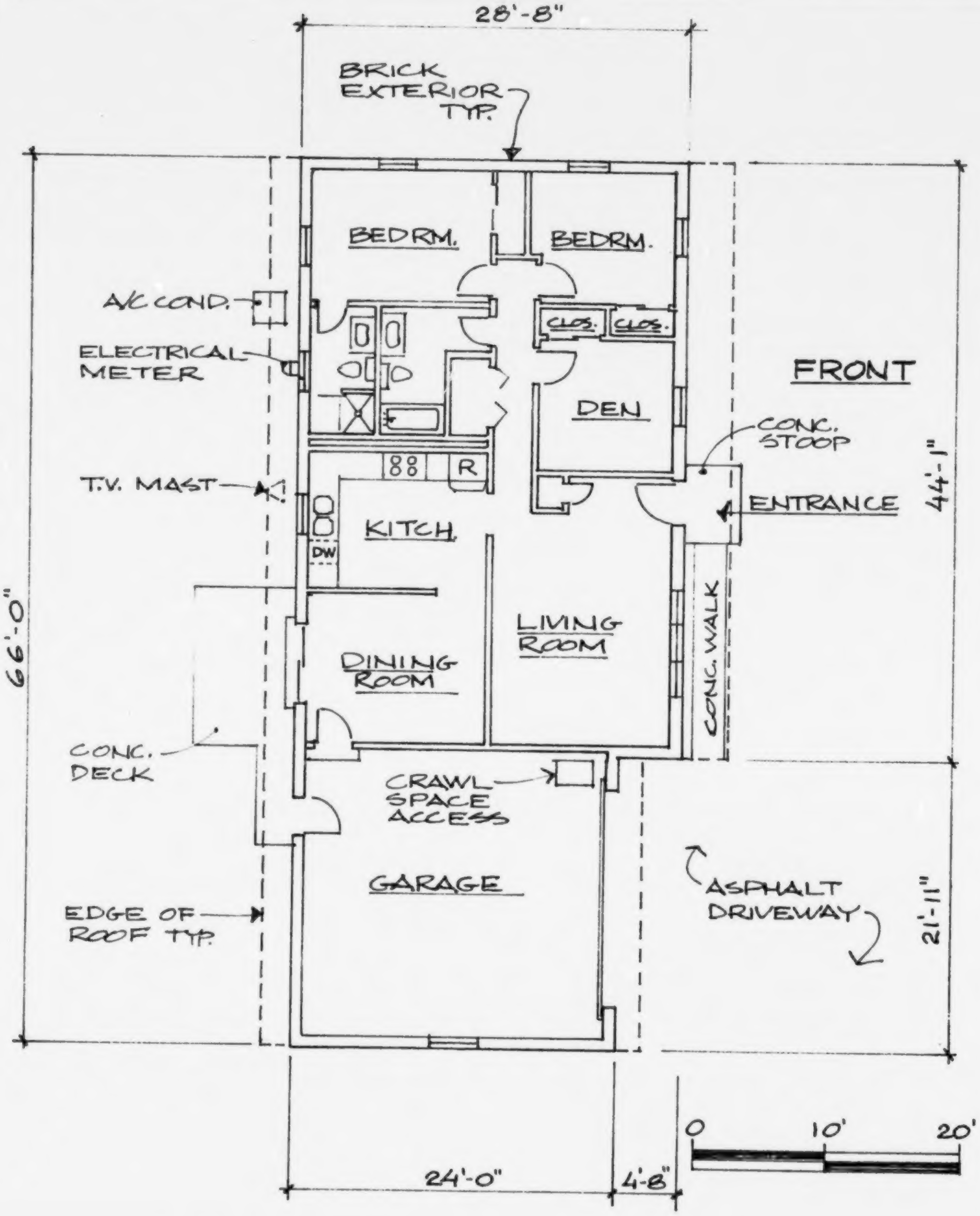


Figure 24-8. Natural crawl-space ventilation, foundation vents open (crawl space)



ACRES Acres International Corporation	LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
	CRAWL SPACE	Date: 3/24/88	24
	House Group: CRAWL SPACE	PHASE:	



ACRES
Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON

HOUSE NUMBER

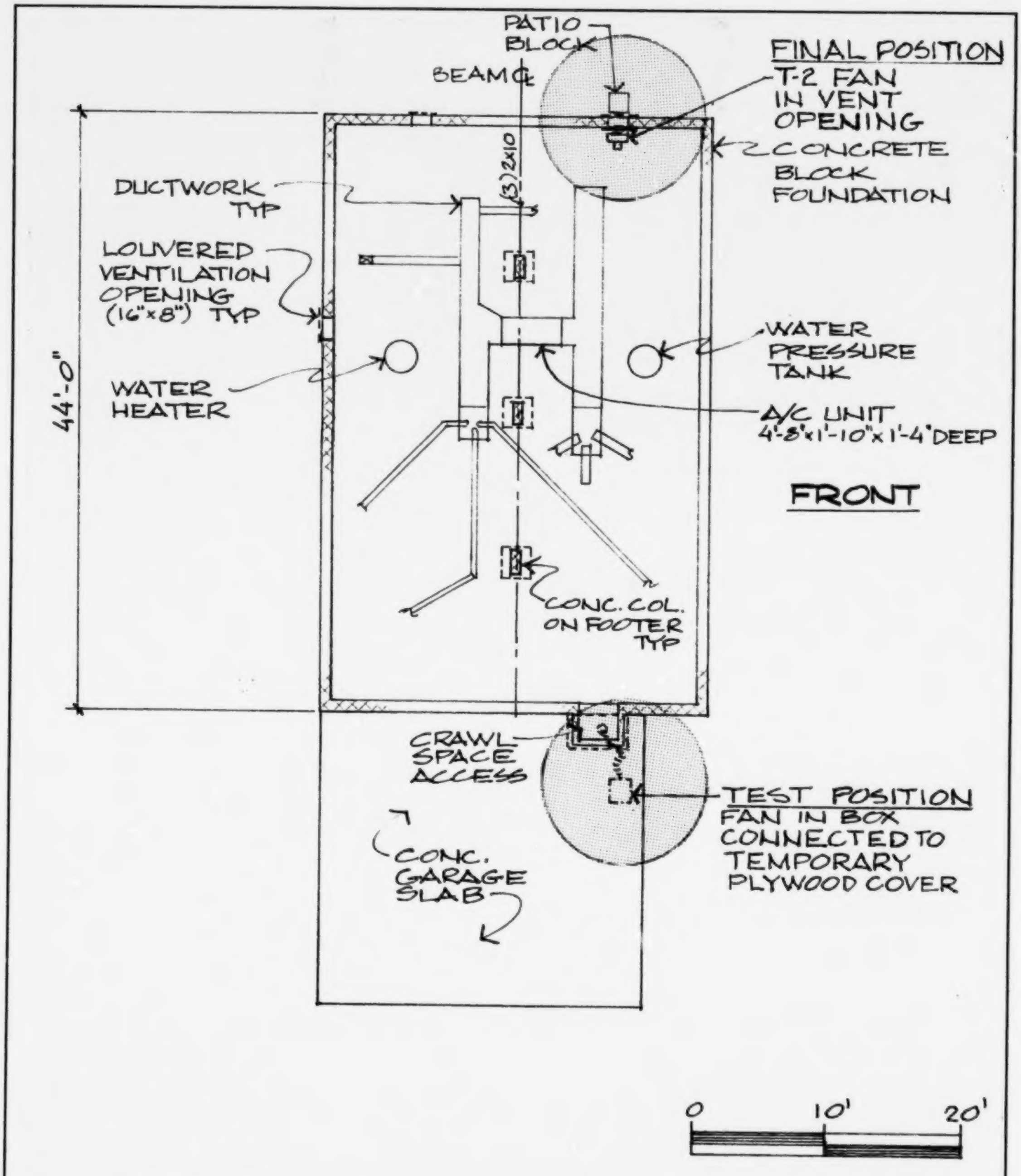
GRADE LEVEL PLAN

Date: 2/25/88

24

House Group: **CRAWL SPACE**

PHASE:



ACRES
Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON

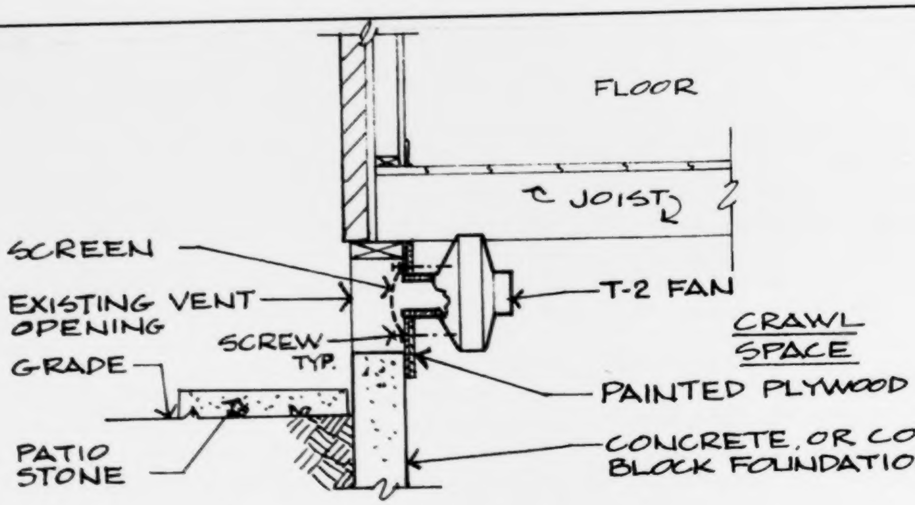
CRAWL SPACE

Mitigation system: CRAWL SPACE VENTILATION

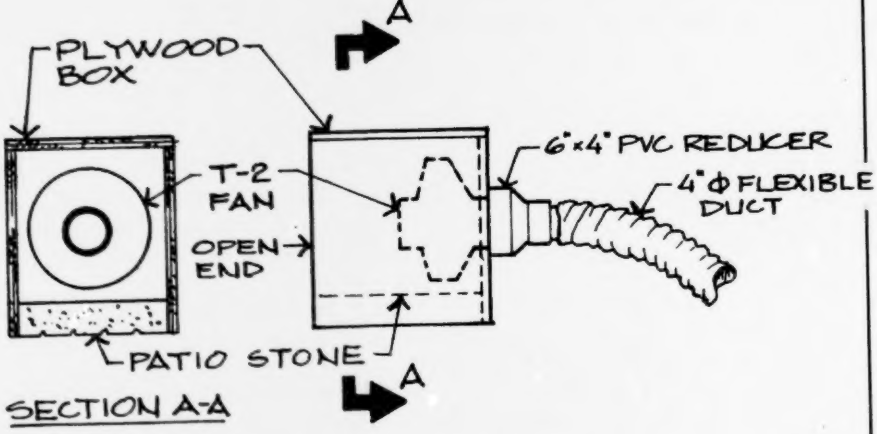
Date: MAY 1988

PHASE: TEST AND FINAL

HOUSE NUMBER 24



FINAL SYSTEM
N.T.S.



TEST SYSTEM
N.T.S.

ACRES Acres International Corporation	LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
	SECTIONS/DETAILS	Date: MAY 1988	24
	Mitigation system: CRAWL SPACE VENTILATION	PHASE: TEST AND FINAL	

HOUSE 28

1 GENERAL DESCRIPTION

This large (190 m^2) single-story crawl-space house with attached garage was built in the early 1960's in a rural subdivision west of Tipp City. The foundation walls are of poured concrete and the exterior walls are of brick. Entry to the crawl space is by a trap door in the garage. The crawl-space earth floor is generally covered with plastic sheets which are underlain with carpet in the entrance area. There are 7 crawl-space foundation wall vents, 40 by 20 cm, closed by pivoting dampers set in window wells, for the exterior grade level is just below the brick siding. There is no insulation between the joists supporting the overhead wooden floor. This floor is constructed of tongue-in-groove hardwood over a diagonal 3" strip wood base and is covered with wall-to-wall carpeting in the living room, hallway and one bedroom. The kitchen and utility room floors are covered with vinyl sheeting on top of vinyl tiles. Water is obtained from a well via a pressure storage tank located in the crawl space. Heating is by a gas-fired hot-water boiler in the garage and baseboard convectors. Connections between the crawl space and the living area include the openings around the hot water pipes to every convector, and around water and sewer pipes.

2 INVESTIGATION

In January 1988, a short-term continuous radon-monitor measurement made as part of the pre-selection process found that concentrations in the crawl space ranged from 17 to 24 pCi/L, averaging 20.5 pCi/L over 19 hours, while concentrations in the living room ranged from 12 to 17 pCi/L, averaging 14.5 pCi/L over 39 hours.

In March 1988, further radon monitoring was conducted with the crawl-space vents closed (the "pre-mitigation" condition). Over a 98-hour period, radon concentrations in the crawl space ranged from 16 to 40 pCi/L, averaging 31.1 pCi/L (Figure 28-4), while concentrations in the living room ranged from 0 to 13 pCi/L, averaging 5.0 pCi/L (Figure 28-3).

Perfluorocarbon tracer (PFT) studies were also conducted in March to measure ventilation and transfer rates with the vents closed. The average ventilation rate over 21 days was for the living space was measured as 0.26 ac/h while that for the crawl space was 0.37 ac/h. The ratio of living-area to crawl-space average concentrations for the tracer released in the crawl space was 0.21 (4.6/22.4). This was close to the radon concentration ratio of 0.16 (5/31).

The foundation vents were opened to provide natural crawl-space ventilation in early April. Radon concentrations in the crawl space ranged from 1 to 8 pCi/L, averaging 4.2 pCi/L over a 93 hour period, while upstairs radon concentrations ranged from 0 to 7 pCi/L, averaging 2.7 pCi/L. Although crawl-space radon had been reduced by 86%, living space radon was only reduced by 46%, for an upstairs/crawl-space radon ratio of 0.64, suggesting that more air was entering the house from the crawl space than when the vents were closed.

Simultaneous PFT measurements were inconsistent, and indicated that the crawl-space ventilation *decreased* from 0.37 to 0.07 ac/h, and a smaller decrease from 0.26 to 0.16 ac/h for the living area. The tracer concentration ratio of 0.08 was much lower than the radon ratio of 0.64.

The vents were then closed, and a temporary fan was connected to a plywood panel placed in the crawl-space entrance to exhaust at 39 L/s. With the fan on, radon concentrations in the crawl space ranged from 13 to 34 pCi/L, averaging 26.1 pCi/L over an 89-hour period, while concentrations in the living area ranged from 0 to 2 pCi/L, averaging 0.8 pCi/L over a 90-hour period. The ratio of living-area to crawl-space radon concentrations was 0.03, suggesting that the effect of the crawl-space exhaust air was largely drawn from the house, and this prevented crawl-space air from entering the living area.

Simultaneous PFT studies indicated that the ventilation rate in the living area was 0.16 ac/h, and the crawl-space ventilation rate was 0.16 ac/h, equivalent to an airflow of 30 m^3/h, much less than the nominal exhaust flow of 140 m^3/h. The tracer concentration ratio of 0.06 is about double the radon ratio of 0.03.

In late May 1988, the crawl space was inspected for installation of a permanent exhaust system. A steam/hot water pipe to a radiator was found to block the preferred vent at one end of the house, the owner agreed to use of a vent midway along the rear wall. The screen and grille were removed, the uneven spaces of the vent/wall were mortared smooth, and a plywood sheet installed. A T-2 in-line centrifugal fan was then mounted on the plywood inside the crawl space, and wiring run to the garage where a speed controller was mounted on the wall.

A hole was drilled with a hand-held auger in the rear of the house. The auger penetrated through clay before refusing on a layer of limestone pebbles at a depth of 150 cm. The owner said that area was one where limestone bedrock was so close to the surface that it was exposed when swimming pools were installed.

3 OTHER MEASUREMENTS

The 1987 charcoal canister test gave a radon concentration of 19.0 pCi/L in the crawl space. A short-term radon-monitor survey in January 1988 found concentrations in the crawl space ranged from 17 to 24 pCi/L, averaging 20.5 pCi/L, while concentrations in the living room ranged from 12 to 17 pCi/L, averaging 14.5 pCi/L.

Pre-mitigation alpha-track measurements with the crawl-space vents closed over the period December 1987 to February 1988 gave average radon concentrations of 13.4 pCi/L in the living area and 21.3 pCi/L in the crawl space.

Alpha-track measurements during the period May to August 1988, with the crawl-space vents open and the exhaust fan off, gave average radon concentrations of 1.7 pCi/L in the living area, and 3.9 pCi/L in the crawl space.

The gamma radiation field in the house ranged from 4 to 5 μR/h, averaging 5 μR/h, whereas the gamma field over the site around the house ranged from 5 to 6 μR/h, averaging 6 μR/h.

MEASUREMENTS SUMMARY FOR HOUSE 28

PYLON AB-5 HOURLY MONITORING

MITIGATION SYSTEM	TEST DATE	TEST STATUS	RADON(pCi/L) RANGE	MEAN	DURATION/ LOCATION	FIG.
pre-selection	01/88		17-24	20.5	19 hrs; CS*	28-1
			12-17	14.5	39 hrs; LR*	28-2
pre-mitigation	03/88	vents closed	16-40	31.1	98 hrs; CS	28-4
		vents closed	0-13	5.0	98 hrs; LR	28-3
natural crawl-space ventilation	03/88	vents open	1- 8	4.2	93 hrs; CS	28-6
		vents open	0- 7	2.7	93 hrs; LR	28-5
crawl-space exhaust	04/88	fan on;DPmax	13-34	26.1	89 hrs; CS	28-7
		fan on;DPmax	0- 2	0.8	90 hrs; LR	28-8

* CS=Crawl Space; LR=Living Room

Average pre-mitigation Pylon results (presented in Tables XII, XIII and 3):

Living area
Weighted average of Figures 28-2 and 28-3 (137 hours total) = 7.7 pCi/L.

Crawl space
Weighted average of Figures 28-1 and 28-4 (117 hours total) = 29.4 pCi/L.

Average post-mitigation Pylon results:

Living area
natural crawl-space ventilation (Table XII) — Fig. 28-5 (93 hr) = 2.7 pCi/L.
forced crawl-space exhaust (Table XIII) — Fig. 28-8 (90 hr) = 0.8 pCi/L.

Crawl space
natural crawl-space ventilation (Table XII) — Fig. 28-6 (93 hr) = 4.2 pCi/L.
forced crawl-space exhaust (Table XIII) — Fig. 28-7 (89 hr) = 26.1 pCi/L.

SYSTEMS MEASUREMENTS

PHASE	MITIGATION SYSTEM	TEST DATE	MEASUREMENTS			COMMENT
			SUCTION (Pa)	FLOW (L/s)	RADON (pCi/L)	
1	crawl-space exhaust	04/88		39		at fan

PFT VENTILATION STUDIES

TEST DATE	CRAWL-SPACE CONDITIONS	VENTILATION RATES				CONCENTRATION RATIO (LIVING/CRAWL)
		LIVING AREA		CRAWL SPACE		
		(m^3/h)	(ac/h)	(m^3/h)	(ac/h)	
3/88	vents closed	115	0.26	69	0.37	4.6/22.4
3-4/88	vents open	70	0.16	13	0.07	6.2/76.8
4/88	exhaust on	68	0.16	30	0.16	2.5/41.3

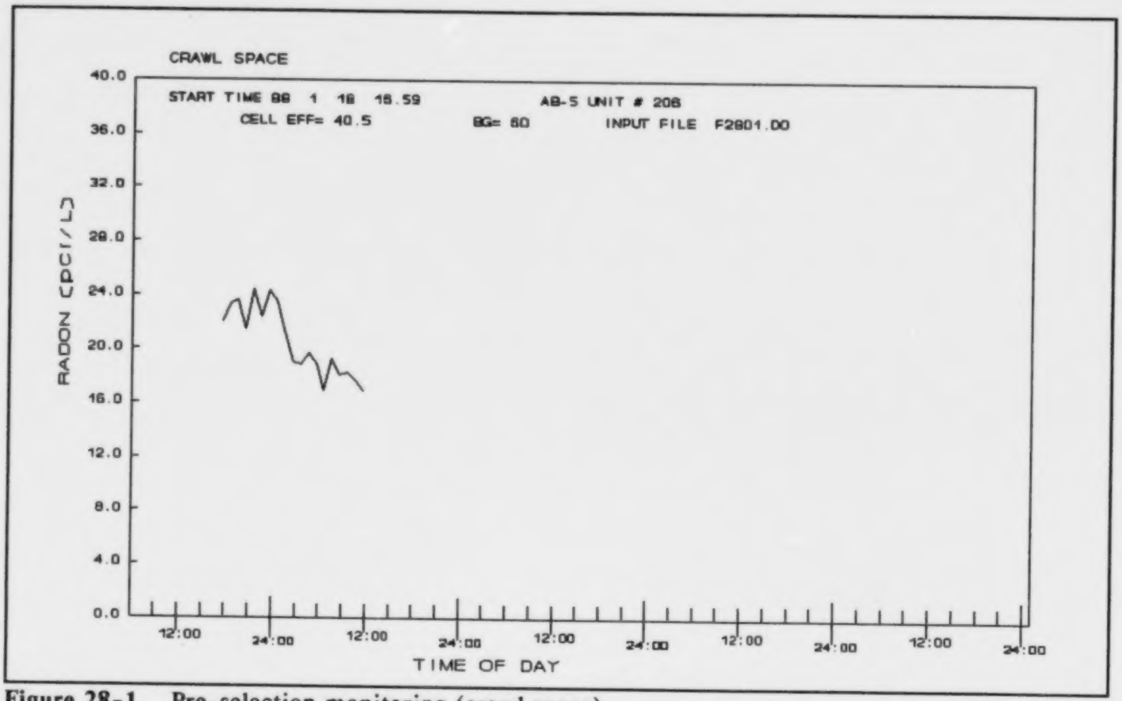


Figure 28-1. Pre-selection monitoring (crawl space)

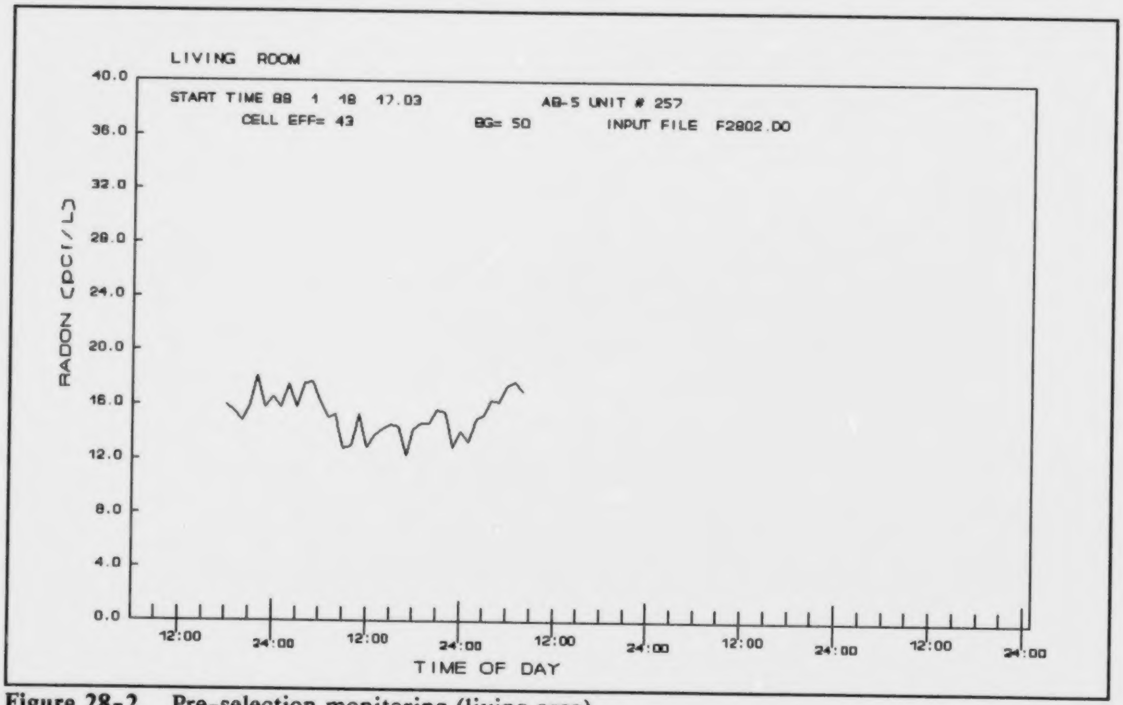


Figure 28-2. Pre-selection monitoring (living area)

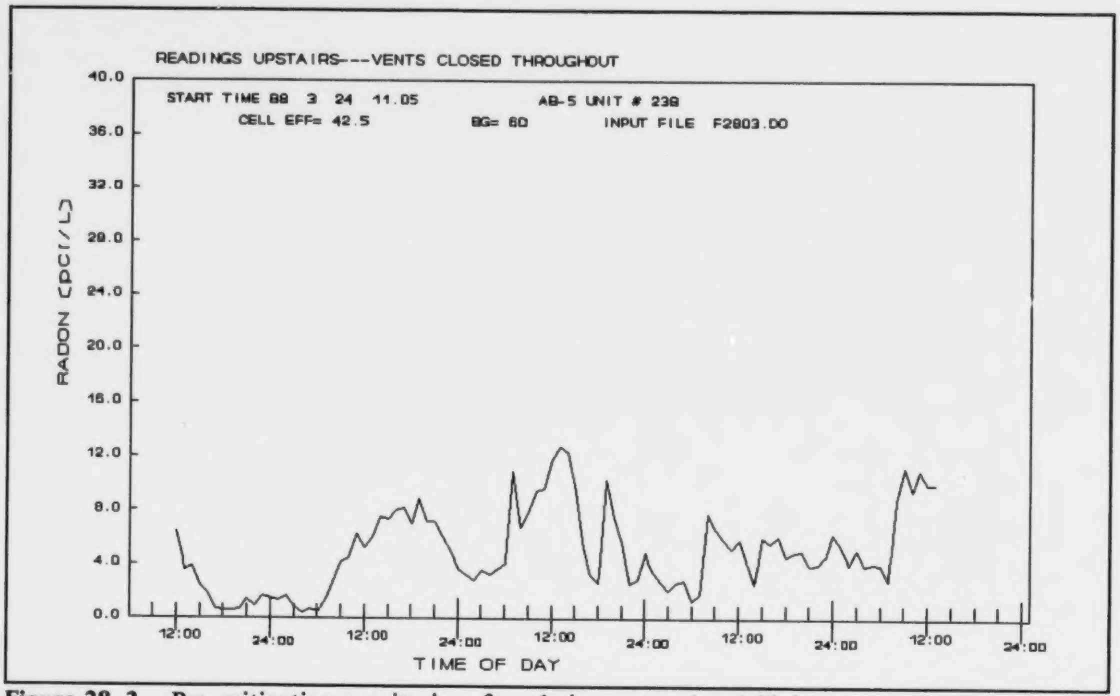


Figure 28-3. Pre-mitigation monitoring, foundation vents closed (living area)

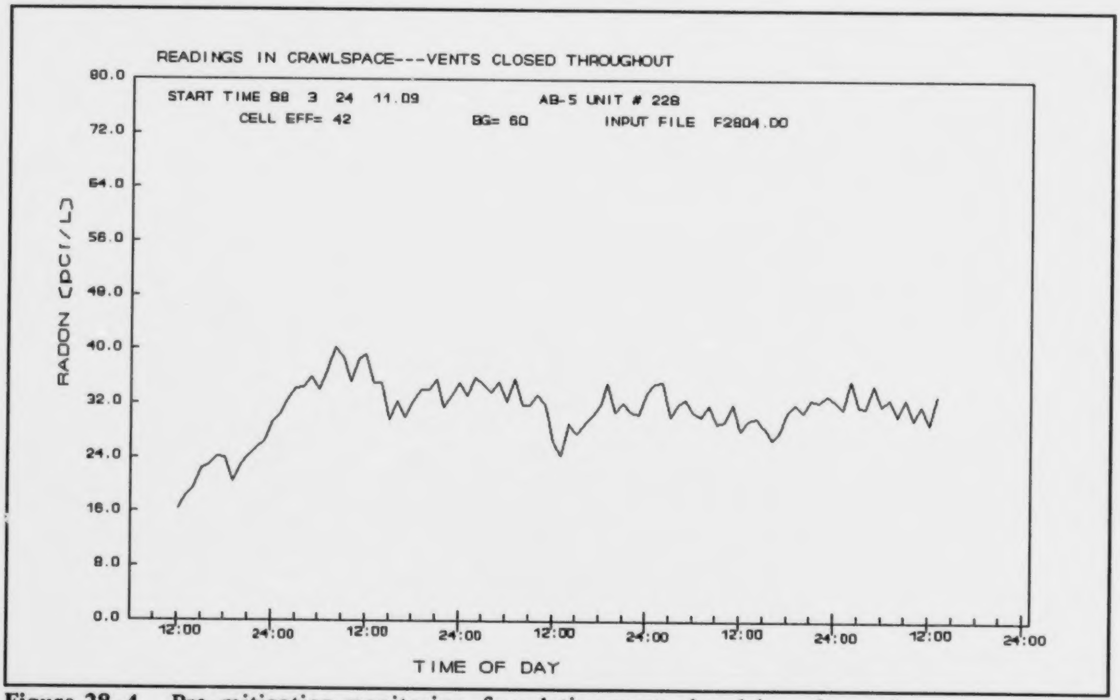


Figure 28-4. Pre-mitigation monitoring, foundation vents closed (crawl space)

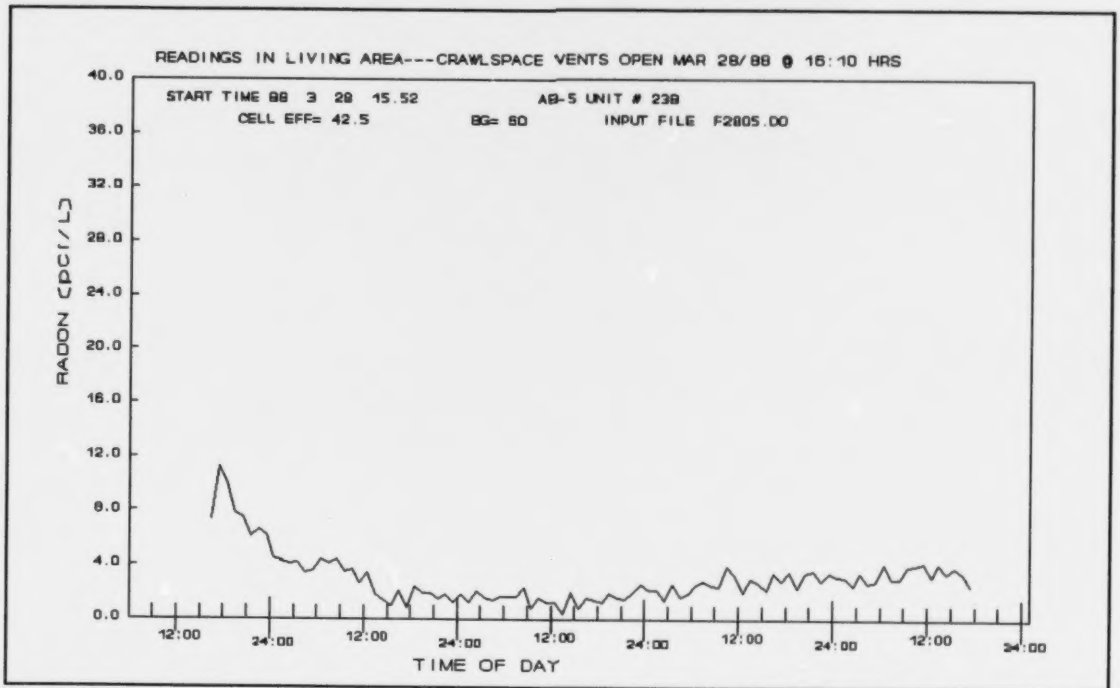


Figure 28-5. Natural crawl-space ventilation, foundation vents open (living area measurement)

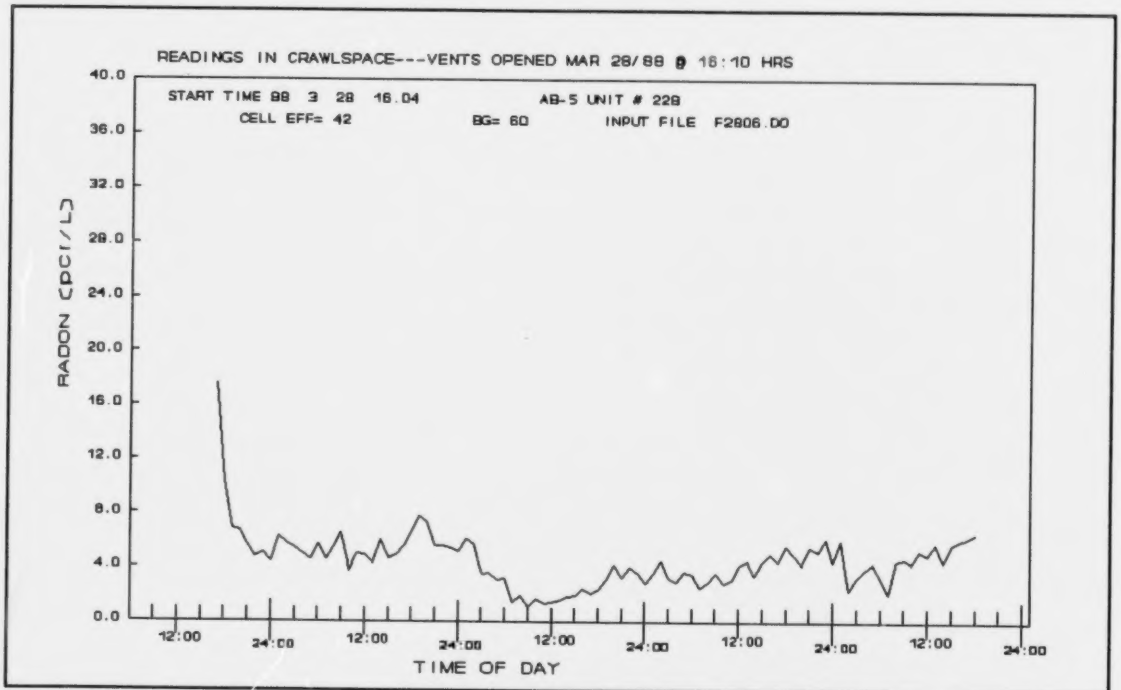


Figure 28-6. Natural crawl-space ventilation, foundation vents open (crawl-space measurement)

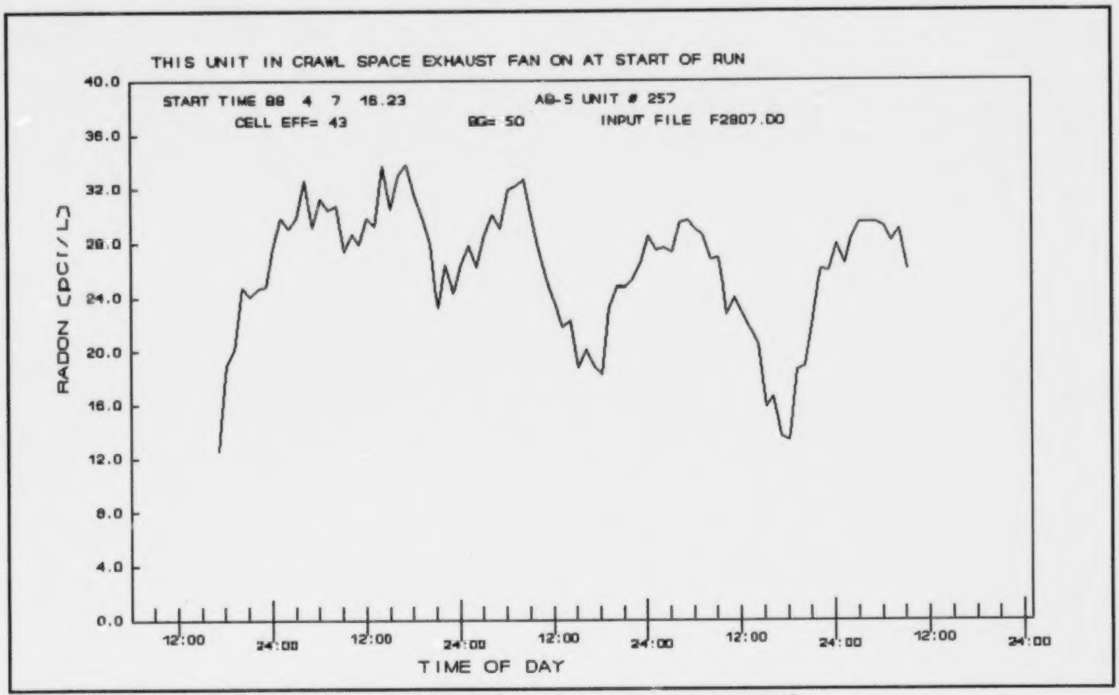


Figure 28-7. Forced crawl-space exhaust (crawl-space measurement)

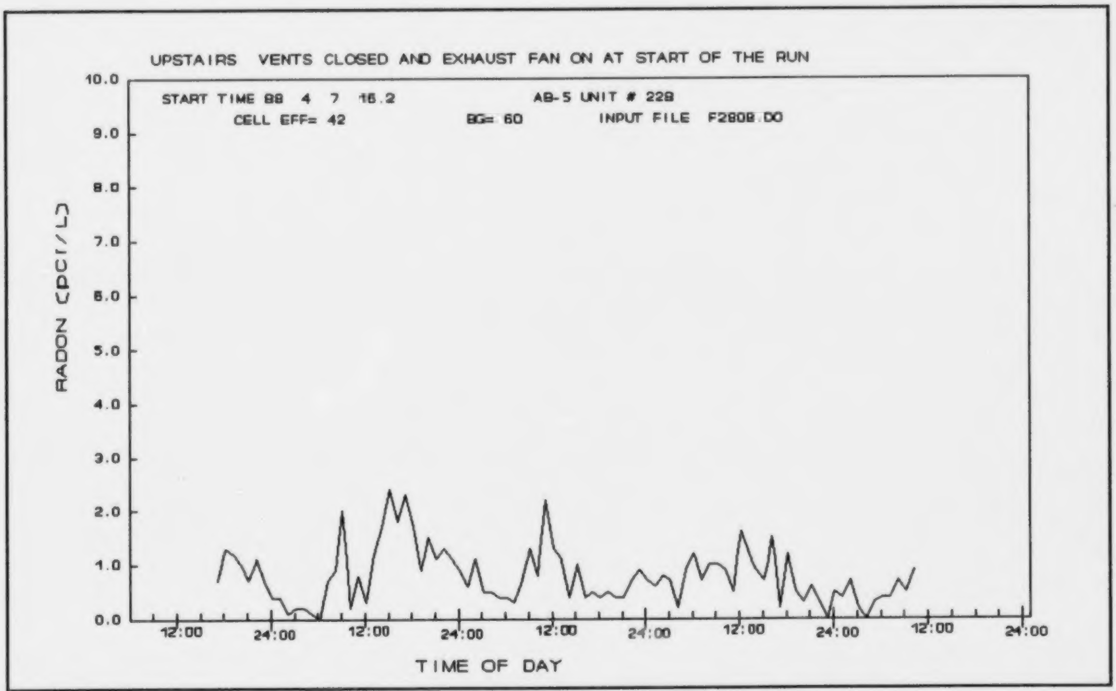
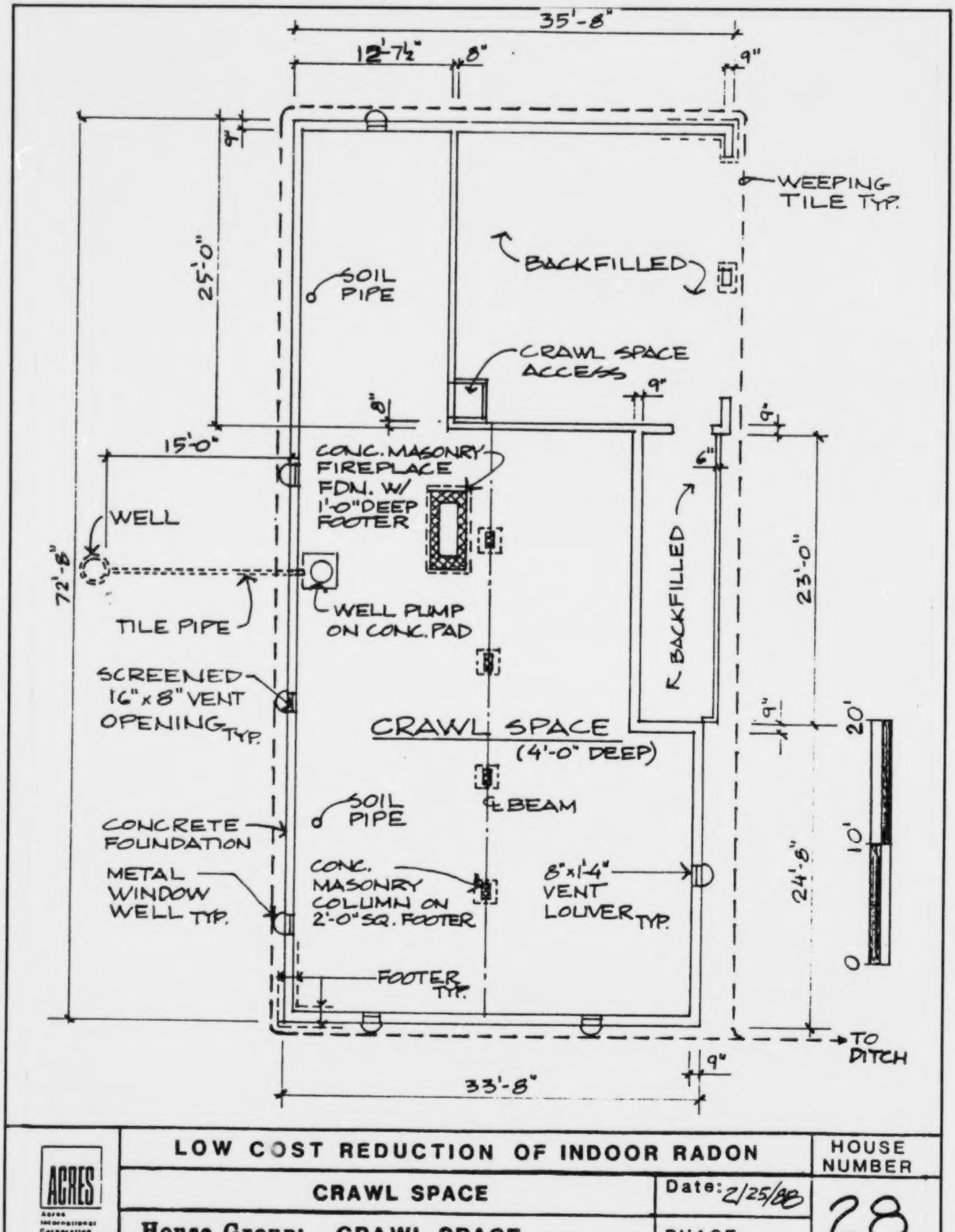


Figure 28-8. Forced crawl-space exhaust (living area measurement)



ACRES
Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON

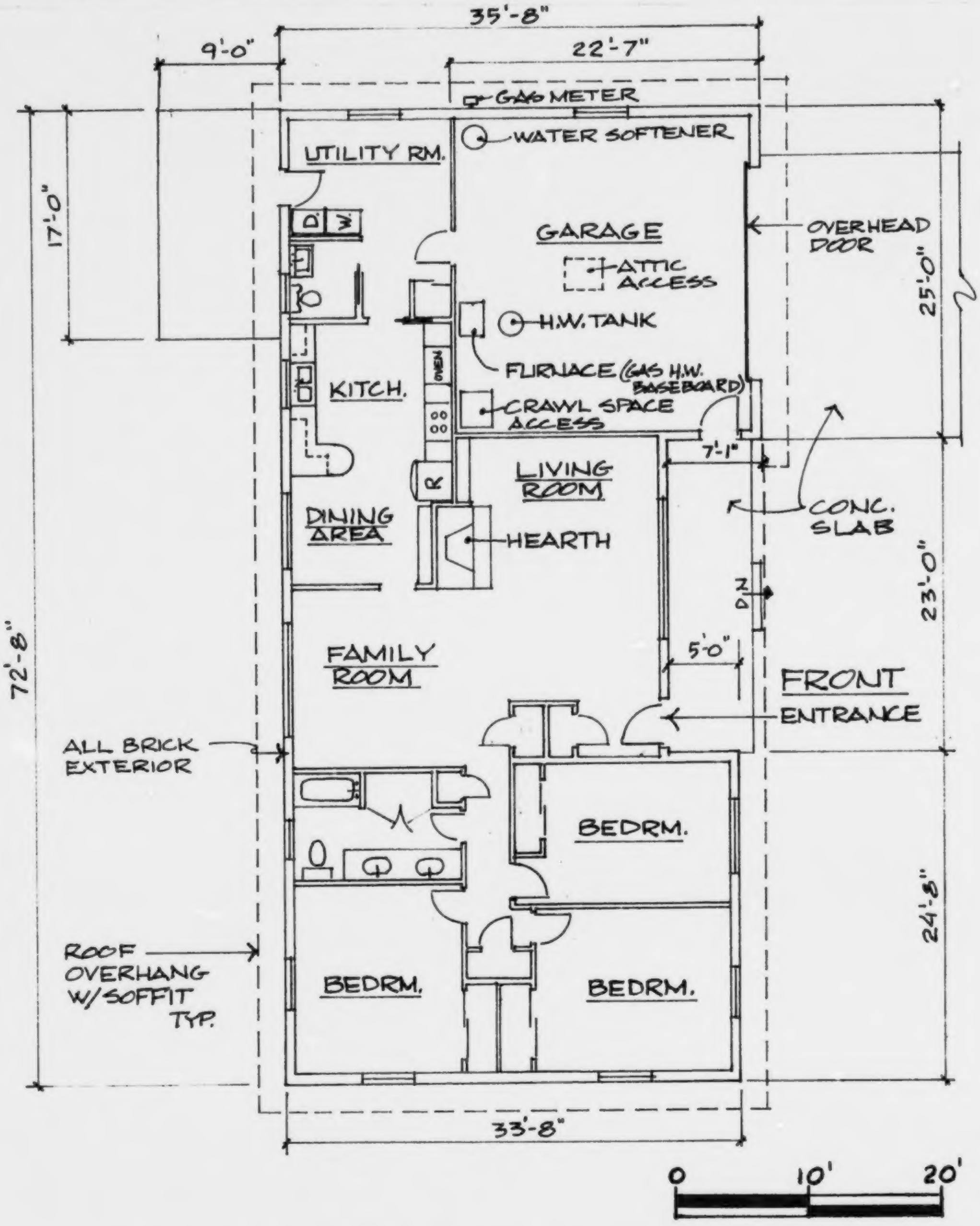
HOUSE NUMBER 28

CRAWL SPACE

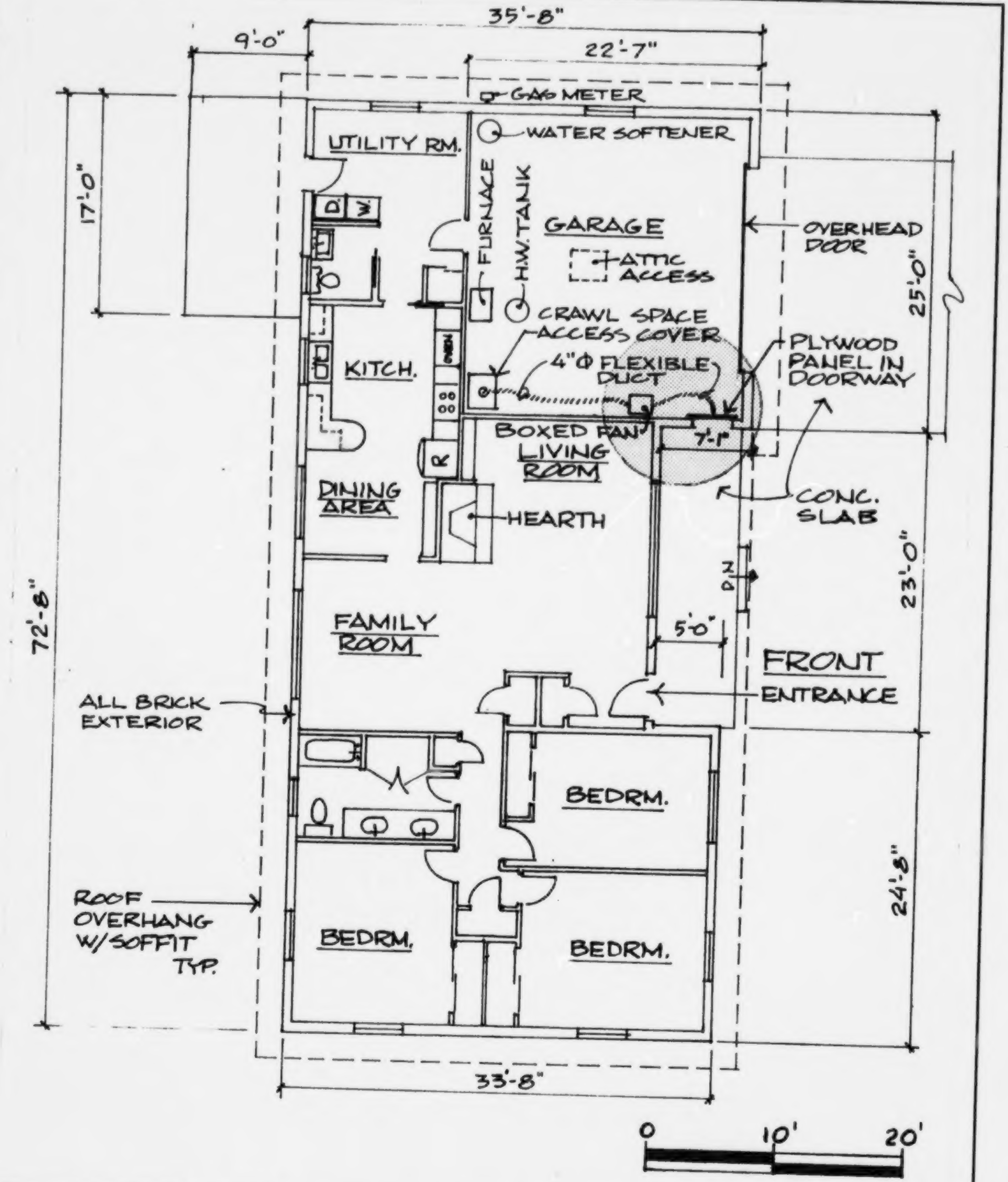
Date: 2/25/88

House Group: CRAWL SPACE

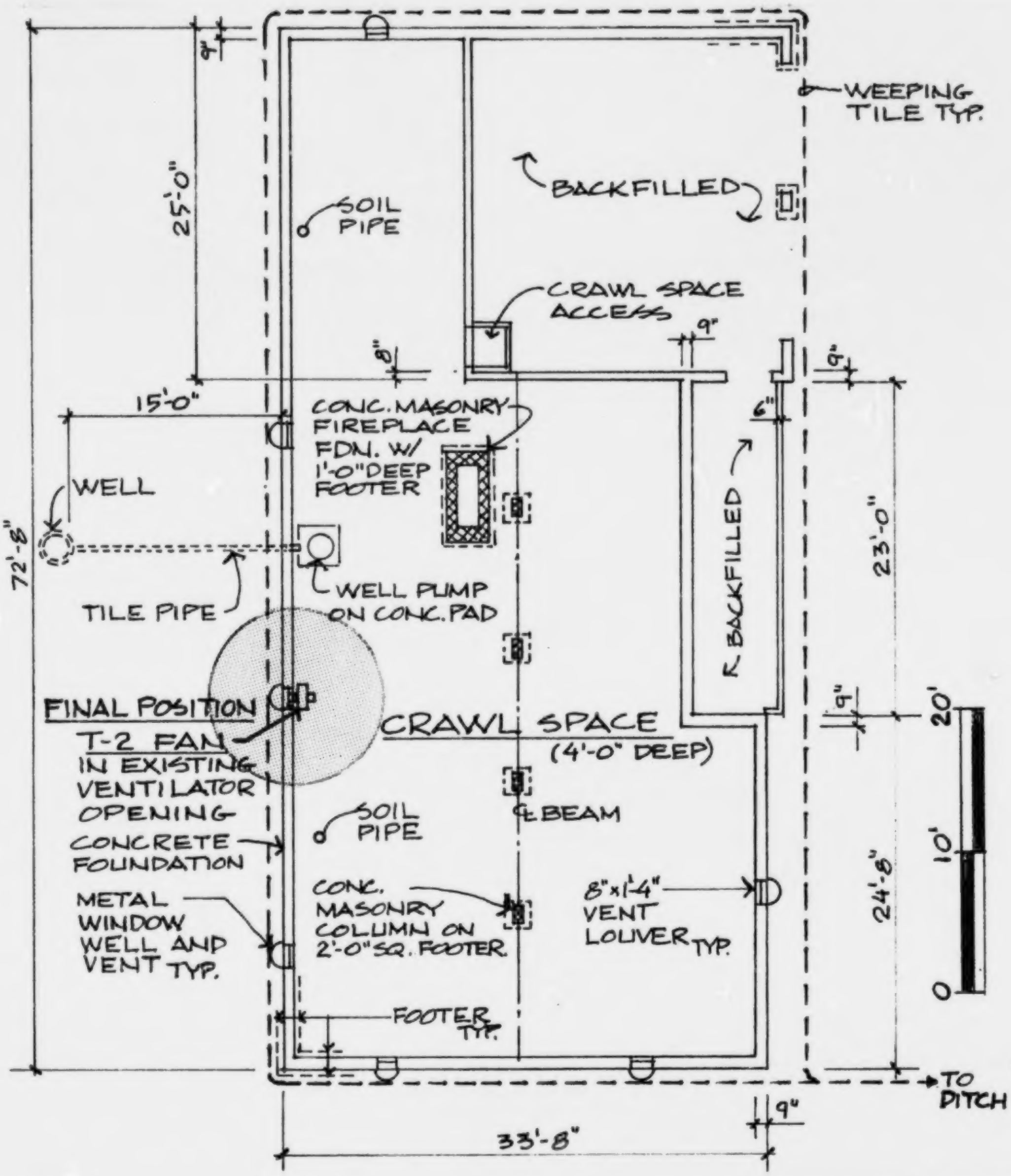
PHASE:



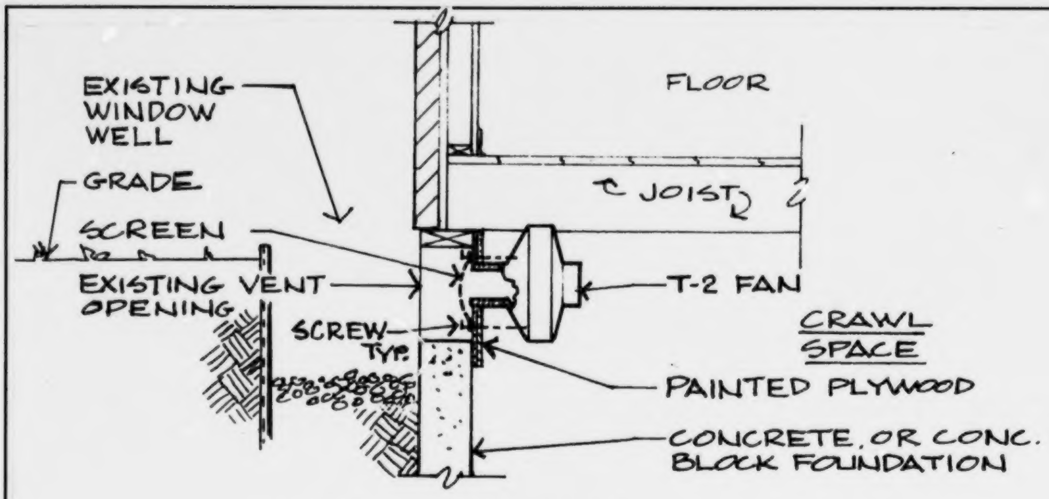
LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
GRADE LEVEL PLAN	Date: 2/25/88	28
House Group: CRAWL SPACE	PHASE:	



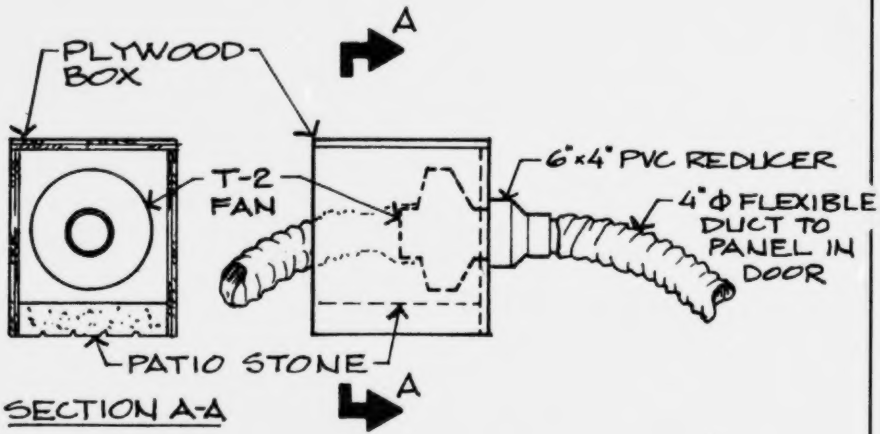
ACRES Acres International Corporation	LOW COST REDUCTION OF INDOOR RADON	HOUSE NUMBER
	GRADE LEVEL PLAN	Date: MAY 1988
	Mitigation system: CRAWL SPACE VENTILATION	PHASE: TEST
		28



ACRES Acres International Corporation	LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
	CRAWL SPACE	Date: MAY 1988	28
	Mitigation system: CRAWL SPACE VENTILATION	PHASE: FINAL	



FINAL SYSTEM
N.T.S.



TEST SYSTEM
N.T.S.

ACRES Acres International Corporation	LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
	SECTIONS/DETAILS	Date: MAY 1988	28
	Mitigation system: CRAWL SPACE VENTILATION	PHASE: TEST AND FINAL	

HOUSE 31

1 GENERAL DESCRIPTION

This small (90 m^2) slab-on-grade house with a detached garage was built in the late 1950's in a suburban subdivision in Fairborn. The foundation wall is of poured concrete, the exterior walls are of brick. The floor in the kitchen, bathroom, and utility room is covered with modern vinyl tile, the remainder is covered with fitted carpet, applied over the original tile. Heating is by a down-draft forced air gas furnace with an air conditioning coil located centrally in the utility room, with clay heat distribution ducts running radially beneath the floor slab to formed concrete register boxes. The boxes are open at the bottom, and the sub-slab gravel fill is visible. There is a large opening through the floor slab beneath the bath, accessible via a panel in the utility room wall.

2 INVESTIGATION

A short-term radon-monitor survey as part of the pre-selection process in January 1988 found radon concentrations in the living room ranged from 11 to 27 pCi/L, averaging 16.4 pCi/L over a period of 40 hours.

In mid January 1988, the role of the sub-slab heating ducts in radon entry to the house was investigated by turning the furnace fan to continuous run. This would pressurize the ducts and so prevent the entry of soil gas into the house via the ducts. It would also pressurize sub-slab gravel by leakage from the ducts, and so decrease the movement of soil gas and radon from the soil into the gravel.

The pressure in the sub-slab gravel with the fan off was slightly higher (<1 Pa) than in the house, and air flows from soil to house were visualized with smoke. With the fan on, the pressure in the sub-slab gravel was 5 Pa in the gravel bed at the edge of the open bath pit, 3 Pa through a gap between the register box and the distribution duct with the grille removed, and increased to 8 Pa (the register box pressure) with the grille replaced. The pressure in the furnace plenum was 25 Pa, and the pressure in the register boxes ranged from 7 to 12 Pa. An air sample from beneath the slab at the register box gave 19 pCi/L. Building shell pressure differentials ranged from 1 to 8 Pa higher than in the house depending on location and wind speed, operation of the kitchen exhaust fan decreased the house pressure by about 4 Pa, and operation of the clothes drier on exhaust decreased the house pressure by about 1 Pa.

Continuous operation of the central furnace circulating fan, in February 1988, had no significant effect on the radon concentration. For two days with the fan cycling normally (on "automatic", radon concentrations in the house varied from 7 to 24 pCi/L, averaging 13.2 pCi/L, but with marked peaking starting at about 8 a.m. each morning (see Figure 31-2). When the fan was turned on to operate continuously, the concentration peaked to 19 pCi/L, and then fell slowly over the next 24 hours to about 8 pCi/L, and then increased slightly to around 11 pCi/L where it remained for 24 hours. The resulting average was 12.8 pCi/L over a 43-hour period. The radon concentration fell rapidly to less than 1 pCi/L immediately after the fan was returned to "auto" operation.

These results suggested that the effect of the fan was to force air with elevated radon content from beneath the slab into the house. There was a large opening in the slab beneath the bath, and so a second test was to fill this opening with expanding urethane foam to reduce the flow of air from the sub-slab fill. When the access panel was opened, the opening and most of the space around the bath was filled with loose mineral wool insulation. Nearly 50 L was removed by hand to expose the gravel. A 2 part urethane foam was used to fill the opening, which was about 500 by 600 mm.

Despite this major reduction in open area, the radon supply into the house was not affected. In February 1988, with the furnace fan operating on "Auto", radon concentrations still ranged from 5 to 20 pCi/L with marked peaking and an average of 9.8 pCi/L. When the fan was turned to continuous run, the pattern of variation in radon concentration was virtually identical to that seen before - a rise to 18, a fall to 9, and then holding at 11 pCi/L, for an average of 13.0 pCi/L (see Figure 31-3). This result suggested that there were other large connections to the sub-slab space, probably the joint between the floor slab and the perimeter wall. This joint lies underneath the sole plate of the interior frame wall, and is not normally accessible or visible.

The sub-slab pressure distribution was investigated by drilling 12 mm holes through the floor at three locations: one in each corner of the house near the front wall (holes A and C), and a central hole near the center line (B). A probe through each hole found that there was about 100 mm of pea gravel beneath the slab, underlain by a soft material (clay). The radial heating ducts divided the sub-slab space into separate zones, but holes B and C were in the same zone. A connectivity test was carried out by applying 5 kPa suction to hole C using an industrial vacuum cleaner. This had no effect on pressures or airflows at hole B, indicating that the gravel bed beneath the slab was not continuous within that zone.

The radon concentration in the sub-slab space was measured at each hole, in February 1988, and was essentially constant at about 100 pCi/L. The pressure differentials across the floor slab with the fan off was very small. Airflows were visualized with smoke, and found to be very slow into the house. When the fan was turned on, the pressure in the house relative to outside was not changed, but the pressure in the sub-slab fill increased. The pressure differences were: A, +1 Pa; B, +3 to +5 Pa; C, <+1 Pa. The register boxes in this house were open at the bottom, exposing the sub-slab gravel fill, so to check if closing this pressurization route would decrease the pressure variations across the slab, the open bottoms of the register boxes were filled with expanding urethane foam. This apparently increased the sub-slab pressure difference, for the pressures were now: A, +1 Pa; B, +7 Pa; C, +3 Pa. The pressure at C could be increased to 5 Pa by closing the nearby register grille, indicating that leakage from the heating duct itself was also pressurizing the space.

Closing the register box bases did not reduce the radon concentrations in the house. The baseline concentration remained around 8 pCi/L, and if anything, the daily peaks were accentuated, reaching 32 pCi/L (see Figure 31-4).

The highly cyclic nature of the radon concentrations was discussed with the owner. A sharp rise in concentration took place each morning between 7.30 and 8.30 h, which coincided with the owners raising the thermostat set point when they got up. This would cause the furnace and the circulating fan to run continuously for some time each morning. A similar rise was seen when the fan was turned to continuous run. The peaks in this house therefore seem to be the result of the increased sub-slab pressure forcing sub-slab space air elevated in radon into the house.

A test hole was drilled at the side of the house to a depth of 80 cm with a power auger. The top 30 cm was an organic clay loam, underlain by a stiff fine-grained clay containing grit. Drilling became progressively more difficult as depth increased, and the auger jammed at a depth of 80 cm.

3 MITIGATION

The mitigation system selected for demonstration at this house was sub-slab ventilation through the foundation wall. The system was planned in two stages, a temporary system to check the effectiveness of the system, followed by a permanent installation.

In late March, following a shallow excavation to 200 mm below grade outside the house, a 100-mm hole was drilled horizontally through the foundation wall at the end of the house remote from the garage, at a height just beneath the under surface of the slab. The hole penetrated into the sub-slab gravel fill. A connection was made to the hole by flexible ducting from a T-2 in-line centrifugal fan mounted in a plywood box.

In March 1988, with the fan providing an air flow of approximately 30 L/s at 210 Pa, and the central circulation fan on "Auto", the sub-slab suction system produced levels ranging from 0 to 1 pCi/L and averaged 0.1 pCi/L over 47 hours. When the circulation fan was set to run continuously, levels rose to range from 5 to 10 pCi/L and average 7.1 pCi/L over 43 hours.

When the fan was reversed to pressurize the sub-slab space, level remained elevated, ranging from 0 to 11 pCi/L, and averaging 4.2 pCi/L over 57 hours, despite the central fan being on "Auto" and the system fan operating at maximum pressure, 245 Pa. Upon returning the system to sub-slab suction at reduced pressure, 135 Pa, leaving the house fan on "Auto", levels in the living room were found to range from 0 to 10 pCi/L and average 2.1 pCi/L over 94 hours (from Figures 31-6, and 31-7).

In mid-April, the temporary system was removed from the end wall and transferred to a location adjacent to the bathroom at the rear of the house to check if sub-slab ventilation could be better applied through the opening in the slab below the bathtub. The foam which had been previously applied to close the opening was cut away and the hardened foam/gravel surface was chipped away to allow a 100-mm-diameter metal sleeve to be imbedded into the gravel below. The opening around the metal sleeve was closed with expanding urethane foam. The sleeve was connected to the fan using flexible (clothes dryer) ducting and the fan exhaust was expelled through a metal duct inserted in a glass-louvered door which had been sealed with polyethylene sheeting and duct tape. The hole through the end foundation wall was patched with cement.

With the fan operating at 220 Pa suction and a flow rate of 16 L/s, radon levels ranged from 0 to 2 pCi/L and averaged 0.8 pCi/L over 35 hours while the central circulation fan was on "Auto". When the circulation fan was set to run continuously, levels rose to range from 0 to 6 pCi/L and averaged 2.9 pCi/L over 18 hours.

The owner was transferred from the Dayton area, and put the house up for sale. Further work was suspended until the house was sold and a new agreement could be reached with the new owner.

4 OTHER MEASUREMENTS

The 1987 charcoal canister test gave a value of 18.0 pCi/L in the main bedroom. A short term radon monitor survey in January 1988 found cyclic radon concentrations in the living room ranged from 11 to 27 pCi/L, averaging 16.4 pCi/L.

Pre-mitigation alpha-track measurements over the period December 1987 to February 1988 gave average radon concentrations of 12.6 pCi/L in the kitchen and 14.0 pCi/L in the bedroom.

Alpha-track measurements over the period May to August 1988 — with no mitigation system in operation, in view of the original owner's departure — gave an average radon concentrations of 9.5 pCi/L in the living area.

The radiation field over the site outside the house ranged from 5 to 8 μR/h, averaging 6 μR/h. The field in the house was 3 to 6 μR/h in the center of the floor slab, increasing to 6 to 8 μR/h in contact with the inner surface of the brick exterior walls.

MEASUREMENTS SUMMARY FOR HOUSE 31

PYLON AB-5 HOURLY MONITORING

MITIGATION SYSTEM	TEST DATE	TEST STATUS	RADON (pCi/L)		DURATION	FIG.
			RANGE	MEAN		
pre-selection	01/88		11-27	16.4	40 hrs	31-1
sub-slab pressurization using HVAC fan	02/88	fan cycling normally (auto)	7-24	13.2	44 hrs	31-2
		fan on continuously	8-19	12.8	43 hrs	31-2
bath-tub opening foamed (+HVAC)	02/88	fan on auto	5-20	9.8	41 hrs	31-3
		fan continuous	9-18	13.0	41 hrs	31-3
+registers foamed	02/88	before foaming; HVAC on auto	4-22	8.7	55 hrs	31-4
		after; auto	0-32	10.1	38 hrs	31-4
sub-slab suction (exterior)	03/88	DPmax; auto	0- 1	0.1	47 hrs	31-5
		DPmax; HVAC on continuously	3-10	7.1	43 hrs	31-5
sub-slab pressure	03/88	DPmax; auto	0-11	4.2	57 hrs	31-6
sub-slab suction (exterior)	03/88	0.5DPmax; auto	0- 3	1.4	20 hrs	31-6
	04/88	0.5DPmax;auto	0-10	2.2	74 hrs	31-7
sub-slab suction (new exterior suction location)	04/88	DPmax; auto	0- 2	0.8	35 hrs	31-8
		DPmax; cont.	0- 6	3.1	18 hrs	31-8

Average pre-mitigation Pylon results (presented in Tables IX, X, XI and 3):

Weighted average of Figures 31-1 and HVAC auto portion of Figure 31-2 (84 hours total) = 14.7 pCi/L.

Average post-mitigation Pylon results:

furnace fan on continuously (Table IX) — HVAC continuous portion of Fig. 31-2 (43 hr) = 12.8 pCi/L.
bathtub opening closed (Table IX) — HVAC auto portion of Fig. 31-3 (41 hr) = 9.8 pCi/L.
furnace fan on after slab closure (Table IX) — HVAC continuous portion of Fig. 31-3 and Fig. 31-4 (134 hours total) = 10.4 pCi/L.
sub-slab suction, fan at DPmax (Table X) — Fig. 31-8 (HVAC auto) (35 hr) = 0.8 pCi/L.

SYSTEMS MEASUREMENTS

PHASE	MITIGATION SYSTEM	TEST DATE	MEASUREMENTS			COMMENT
			SUCTION (Pa)	FLOW (L/s)	RADON (pCi/L)	
1	sub-slab pressure (HVAC fan)	02/88				fan off:
			-1*			across slab
			-4			across rear door
			-2			across front door
						fan on:-
			-25			at plenum
			-5			below tub
						register/grille:-
			-3		19	through/off
			-8			through/on
			-17			in/closed
			-7			in/open
			-12			in an other/open
1	registers foamed (+ previous foam below tub + HVAC fan on throughout)	02/88	-1		85	at hole A; before
			-4-5		95	at hole B; before
			0		120	at hole C; before
			-1			at hole A; after
			-7			at hole B; after
			-2-5			at hole C; after
			4900			suction at hole C
			0			at hole B
1	sub-slab suction (exterior)	03/88	210	~30		at fan; DPmax
		03/88	245			at fan; DPmax
			135			at fan; 0.5DPmax
		04/88	220	16		at fan; DPmax

* "Negative suction" denotes pressurization relative to house.

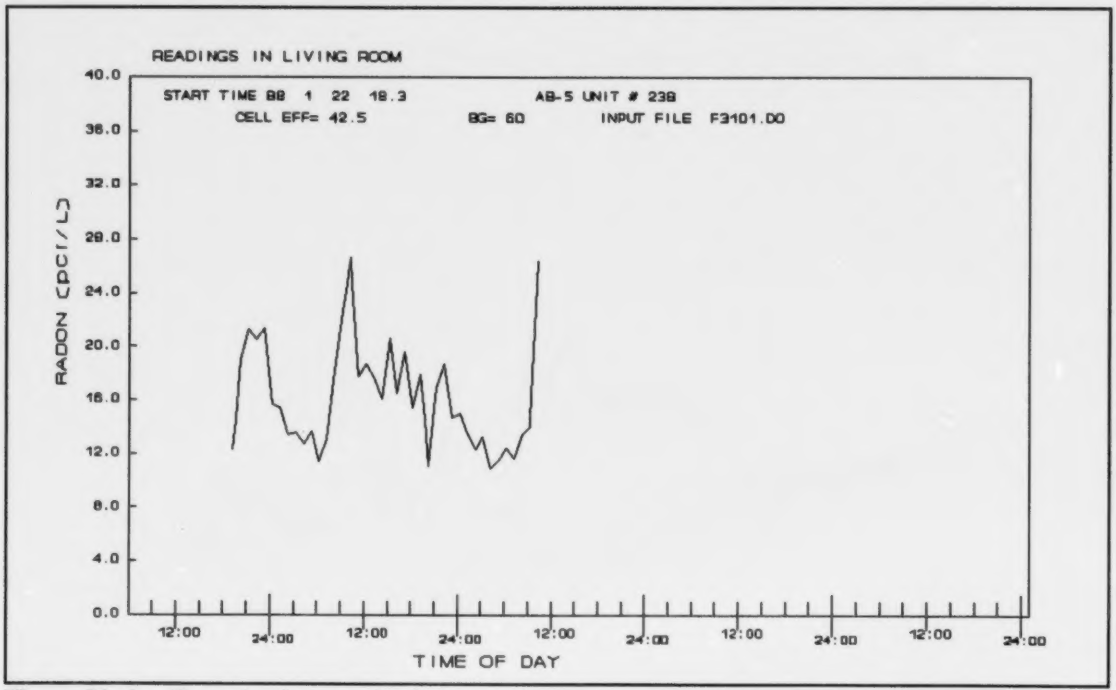


Figure 31-1. Pre-selection monitoring

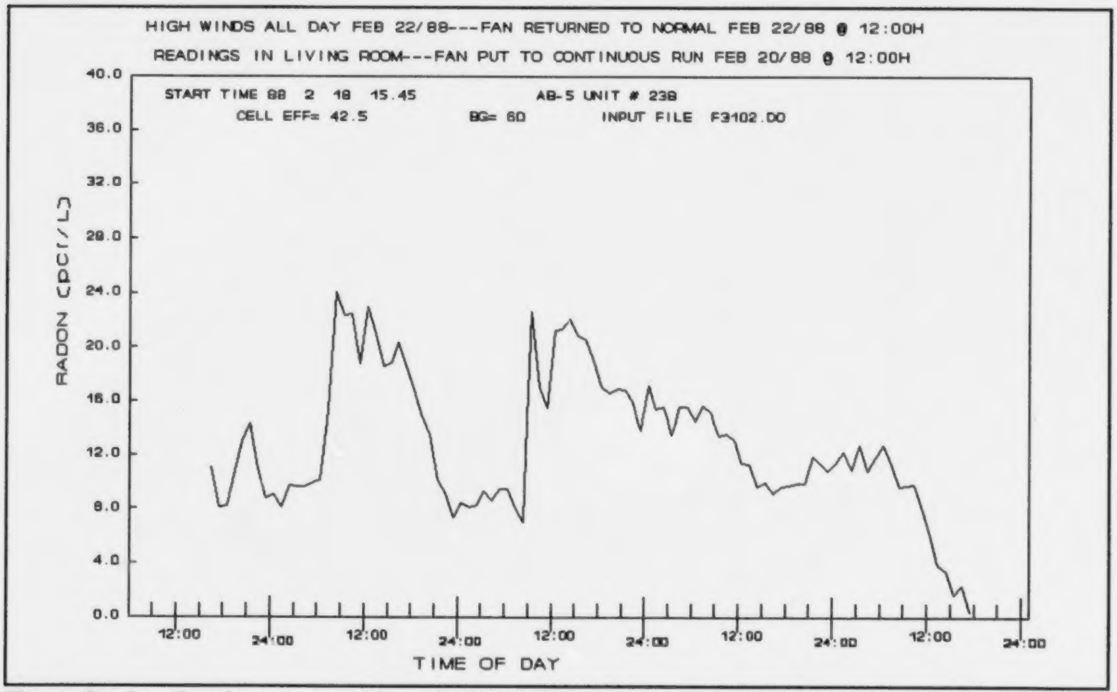


Figure 31-2. Continuous operation of central HVAC fan, vs. normal cycling

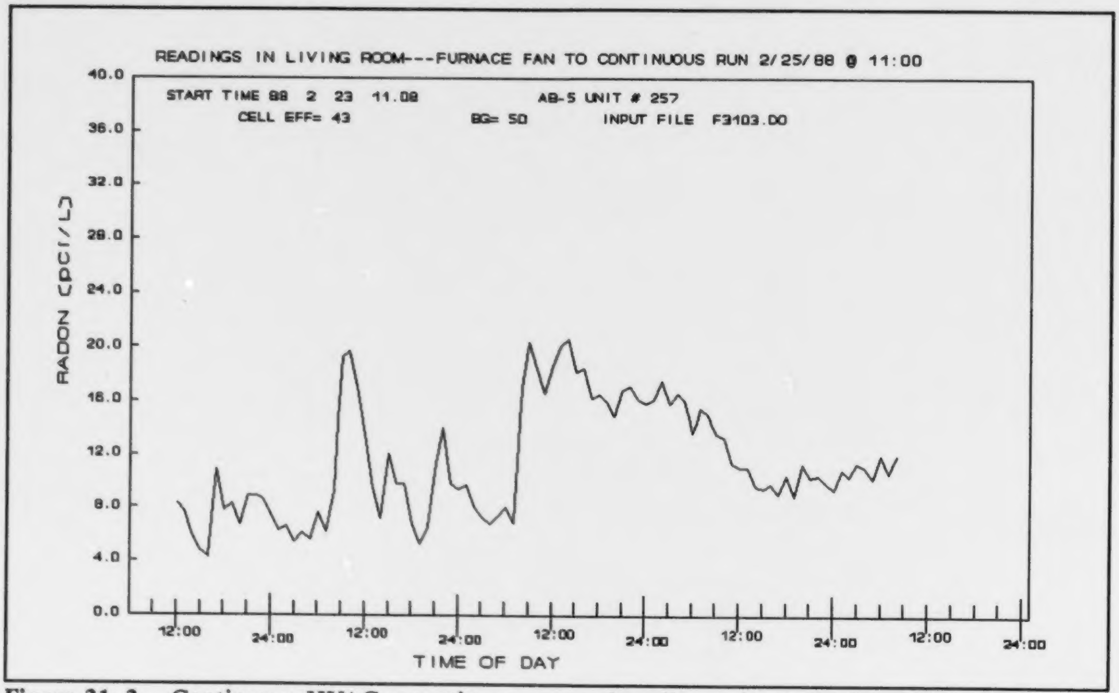


Figure 31-3. Continuous HVAC operation vs. normal cycling, with bathtub opening closed

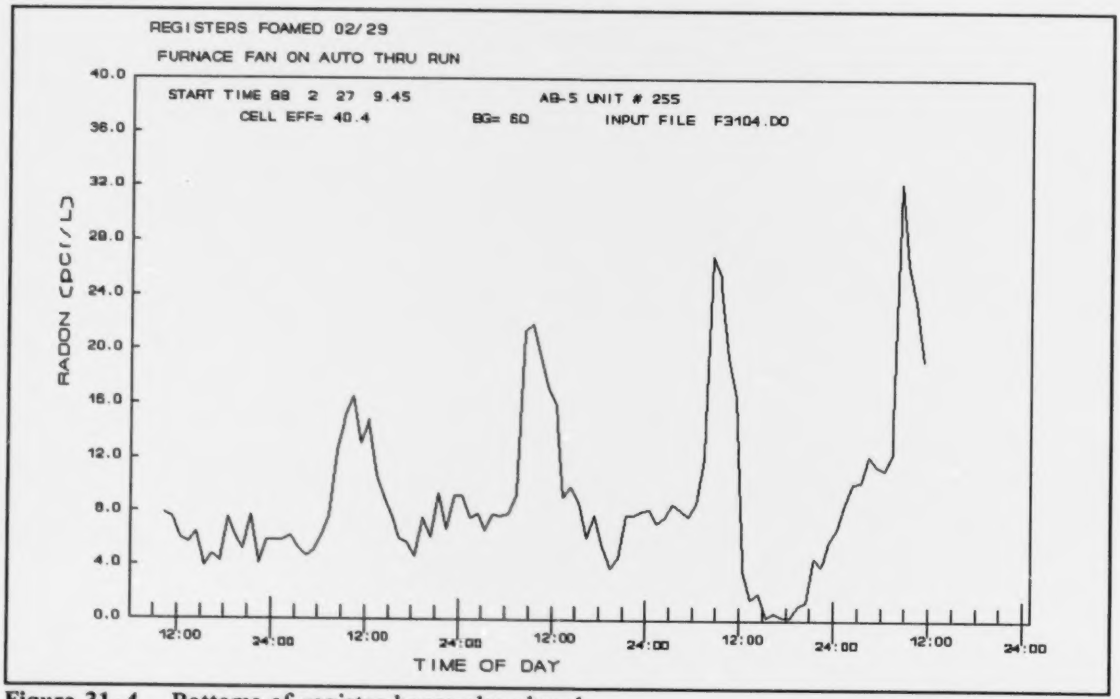


Figure 31-4. Bottoms of register boxes also closed

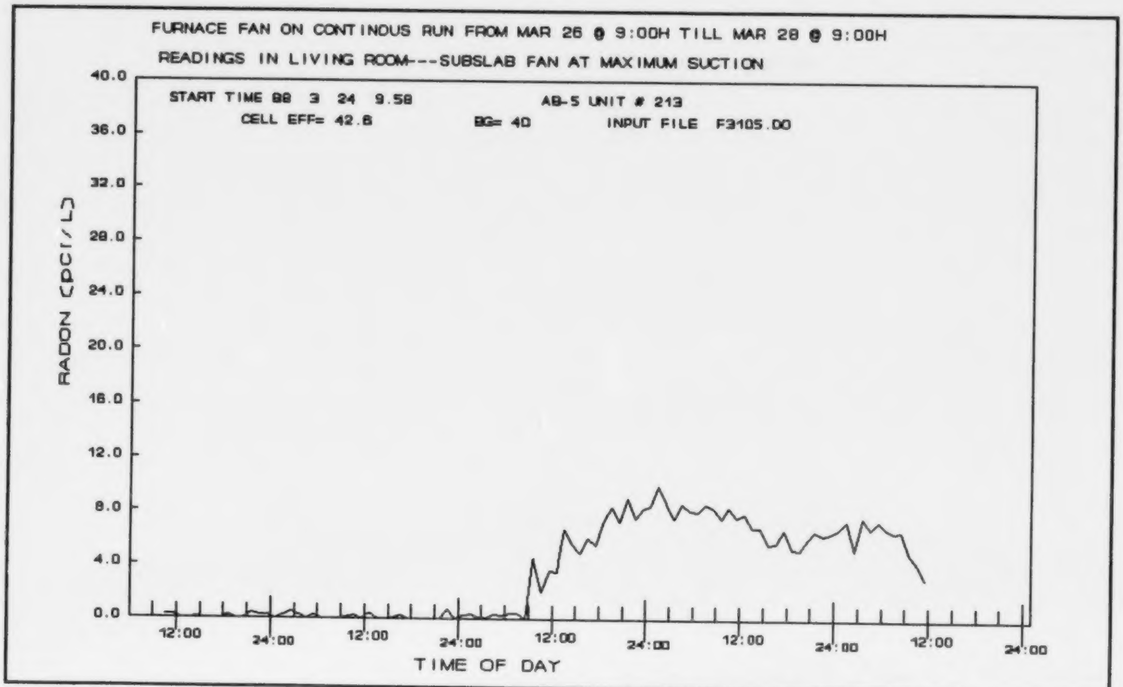


Figure 31-5. Sub-slab suction with exterior point, with and without continuous HVAC operation

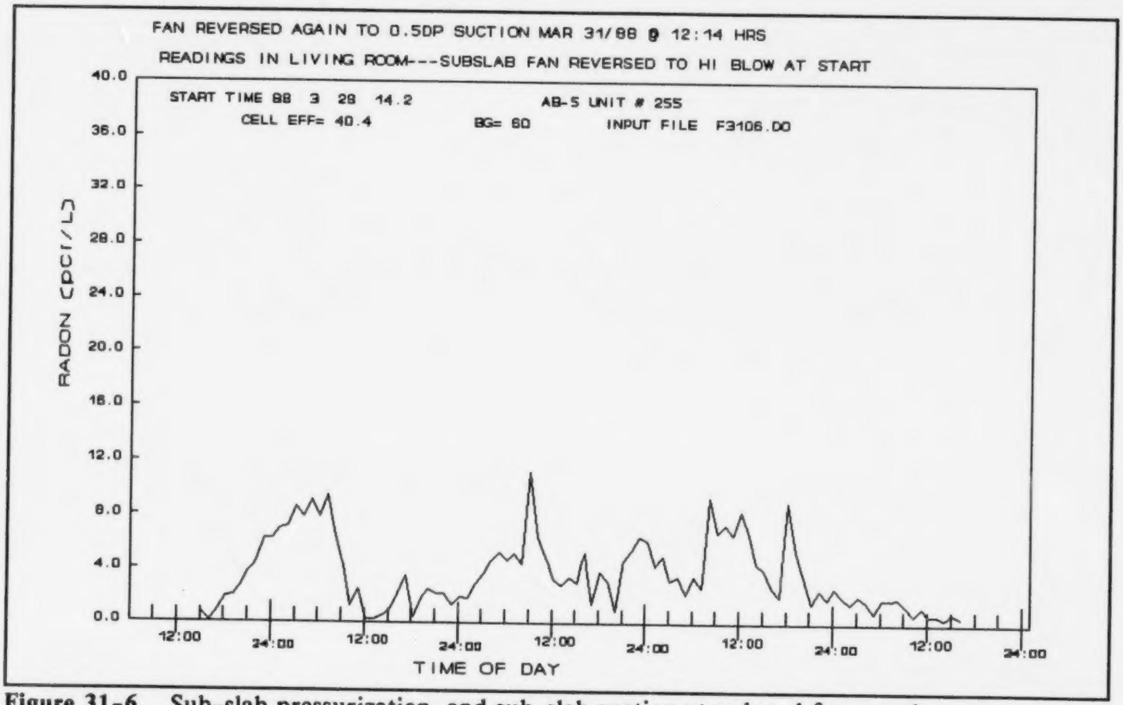


Figure 31-6. Sub-slab pressurization, and sub-slab suction at reduced fan speed

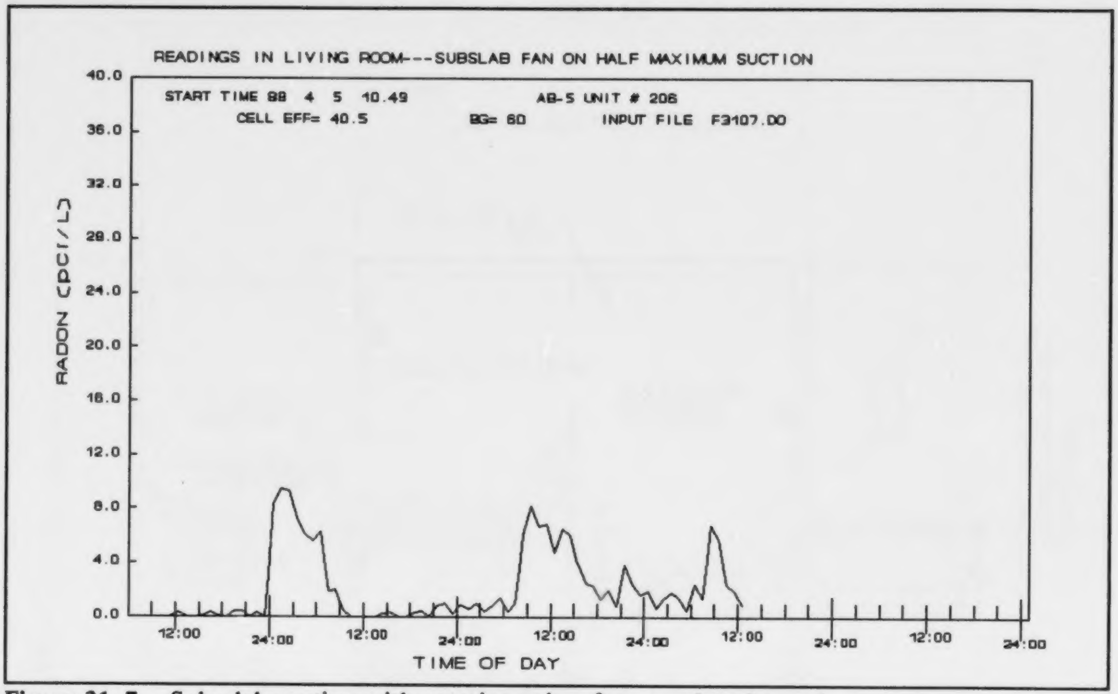


Figure 31-7. Sub-slab suction with exterior point, fan at reduced speed

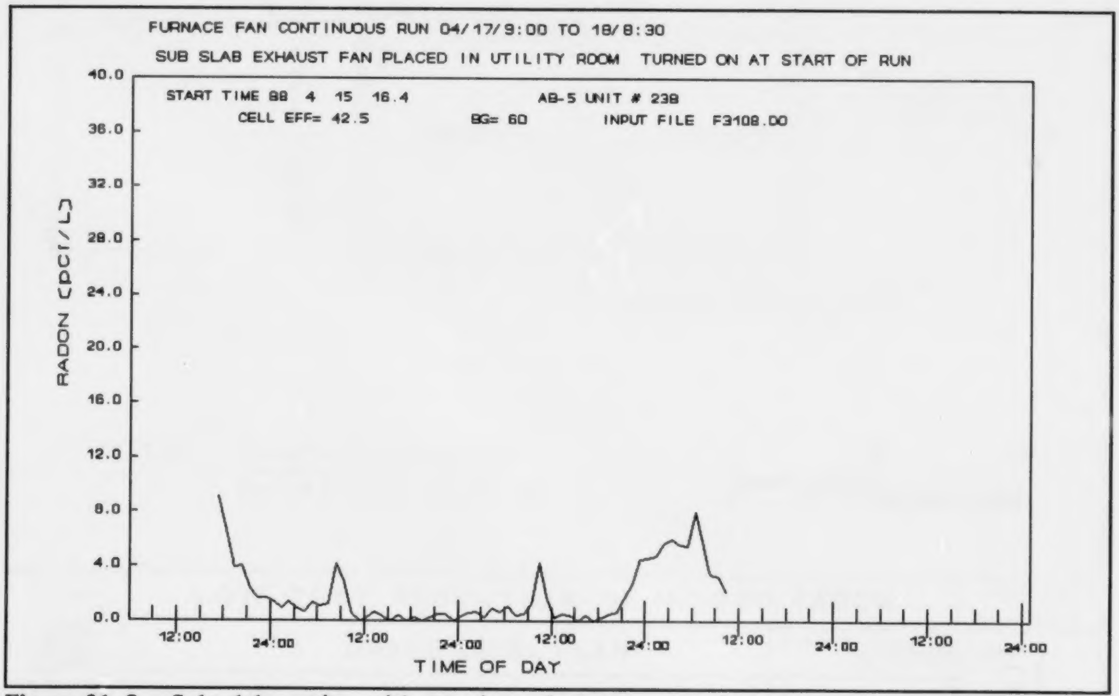
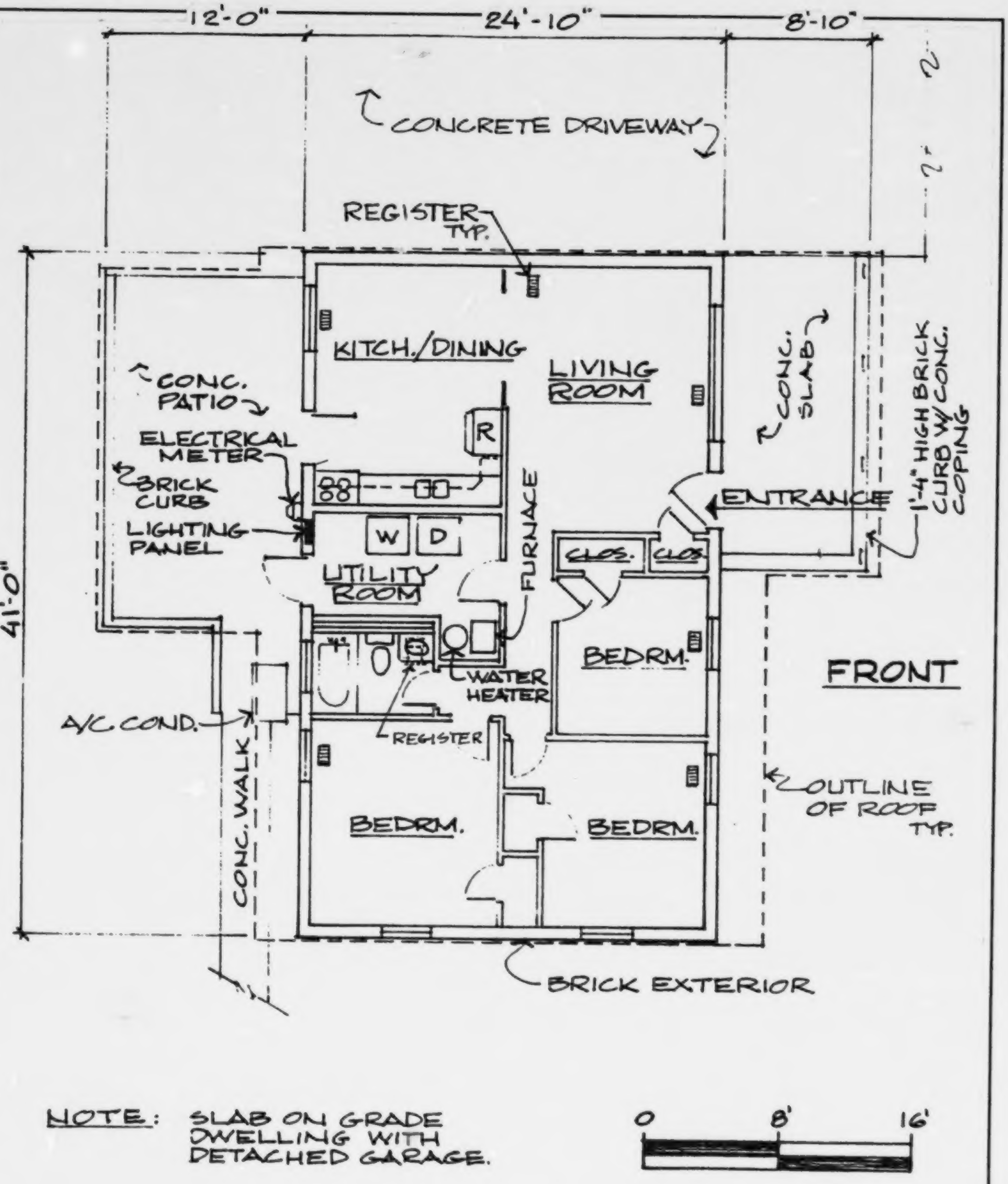
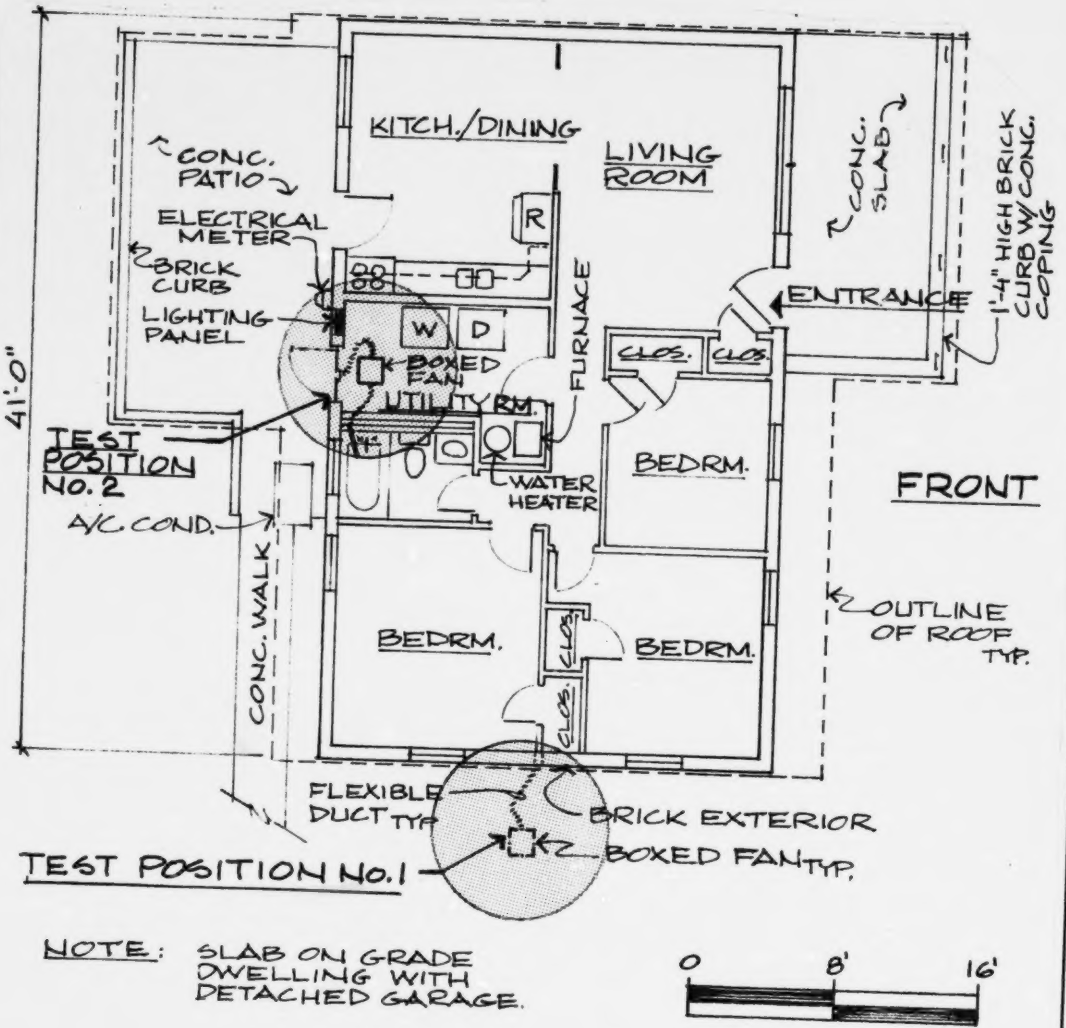


Figure 31-8. Sub-slab suction with exterior point at new location



NOTE: SLAB ON GRADE DWELLING WITH DETACHED GARAGE.

ACRES	LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
	GRADE LEVEL PLAN	Date: 2/23/88	31
	House Group: SLAB ON GRADE	PHASE:	



NOTE: SLAB ON GRADE
DWELLING WITH
DETACHED GARAGE.

ACRES
Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON

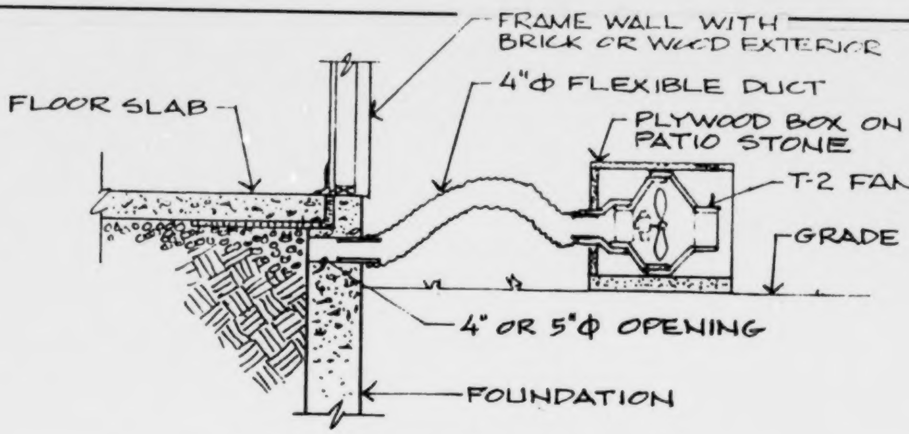
GRADE LEVEL PLAN

Mitigation system: SUB-SLAB SUCTION

Date: MAY 1988

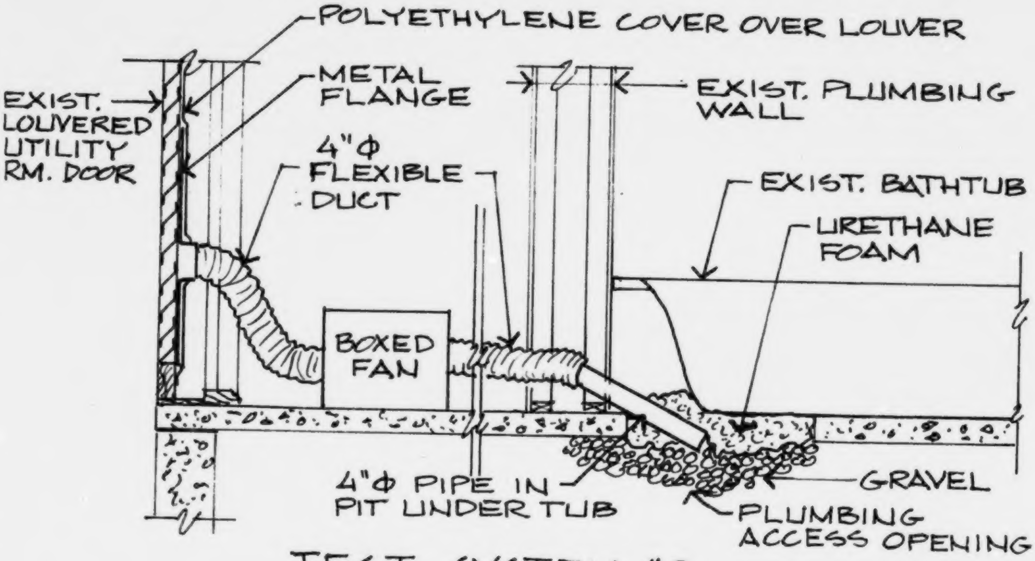
PHASE: TEST 1 AND 2

HOUSE NUMBER 31



TEST SYSTEM #1

N.T.S.



TEST SYSTEM #2 N.T.S.

NOTE: HOUSE 31 SOLD.
FINAL SYSTEM NOT
INSTALLED

ACRES Acres International Corporation	LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
	SECTIONS/DETAILS	Date: MAY 1988	31
	Mitigation system: SUB-SLAB SUCTION	PHASE: TEST	

HOUSE 32

1 GENERAL DESCRIPTION

This large (190 m^2) two-story basement house with attached garage was built in 1987 in a rural subdivision of Fairborn. The basement foundation wall is of poured concrete and the exterior walls are of brick. The basement is unfinished, and there is aluminum-foil-backed glass-fibre insulation applied to the upper 1.2 m of the basement wall. The wall/floor joint is open (up to 4 mm) and there is one major floor crack 1.5 m long, 4 mm wide, across the entrance to a recess that supports the upper floor fireplace. Heating is by an upflow forced-air electric furnace, with air conditioning, and metal air distribution ducts run along the basement ceiling. A sump is located in one corner of the basement is connected to an internal weeping-tile loop, with two drain tiles visible entering the sump. The slab is penetrated by sewer and water pipes and a sewer clean-out.

2 INVESTIGATION

A short-term radon-monitor survey as part of the pre-selection process in January 1988 found concentrations in the basement ranged from 12 to 34 pCi/L, averaging 24.4 pCi/L over 77 hours.

An EPA pre-selection visit was carried out in January 1988. Grab sampling indicated radon concentrations of 250 pCi/L in the sump, 24 pCi/L for the basement air, 96 pCi/L in the opening around the sewer line penetration through the slab, and 25 pCi/L for the floor drain which receives AC condensate and water-heater overflow. These results were largely supported by 30-second sniffer samples collected by a Pylon AB-5. Extensive freon-transport and smoke testing was conducted for the two tile entries to the sump and the 1 to 5-mm wall/floor joint. In particular, good communication between the tile entries was shown by suction on one entry causing immediate flow of smoke into the other.

In February 1988, a temporary sump cover was fashioned from an inverted plastic trash can sealed with closed-cell expanding foam. The sump cover had no effect on the basement radon levels which before closure ranged from 23 to 37 pCi/L, averaging 31.0 pCi/L over 49 hours, and after closure ranged from 16 to 49 pCi/L, averaging 29.2 pCi/L over 40 hours.

To investigate sub-slab communication a 30-mm hole (hole 1) was drilled through the slab in the center of one half of the basement. A grab sample of the undisturbed sub-slab air showed a radon concentration of 900 pCi/L. When suction of 250 to 500 Pa was applied at hole 1 smoke was drawn into a nearby floor crack and several sections of the perimeter wall/floor joint. However, no effect was observed at a 12-mm hole (hole 2) drilled through the slab several meters away in the other half of the basement. Following the suction tests, radon sampled from hole 2 measured 170 pCi/L.

3 MITIGATION

Two mitigation systems were chosen for demonstration at this house. The first system was sub-slab ventilation via the sump. This system was planned in two stages; a temporary system to check the effectiveness of the system, followed by a permanent installation. As this basement was completely unfinished, had solid concrete walls and the wall/floor joint was accessible, the second system chosen was caulking of the open joints in the basement.

3.1 Sub-slab Ventilation via the Sump

At the end of February 1988, a temporary sump ventilation system was installed, with the inverted plastic trash can as sump cover and a 4-inch thin-walled plastic pipe as riser, both sealed in place by expanding foam. The piping extended to a nearby window where a T-2 in-line plastic-bodied fan was mounted through a plywood insert to which a fan-speed controller was screwed. Before suction was applied to the sump, levels in the basement ranged from 22 to 32 pCi/L and averaged 28.6 pCi/L over 5 hours. With the fan operating at maximum setting and drawing air at 87 L/s under 180 Pa suction, radon levels were quickly reduced to range from 0 to 2 pCi/L and average 1.3 pCi/L over 43 hours. Essentially identical results of 0 to 2 pCi/L and average 1.0 pCi/L were obtained with the fan drawing 76 L/s at the reduced pressure of 130 Pa.

When the fan was reversed to investigate the effects of pressurizing the sump, it was found that the maximum flow rate was 87 L/s at 130 Pa, and radon concentrations ranged between 1 and 12 pCi/L, averaging 2.9 pCi/L over 69 hours. When the fan was turned off, levels rose to range from 12 to 22 pCi/L and average 18.5 pCi/L over 19 hours.

A return to sump suction at reduced speed — giving suctions of 80 Pa in the system piping and a flow rate of 58 L/s — reduced levels once more to 1 to 3 pCi/L, averaging 1.5 pCi/L over 41 hours. In these circumstances, the actual suction achieved inside the sump was 55 Pa. When the fan was set at maximum suction, the pressure difference and flow rate measured in the exhaust riser were 160 Pa and 76 L/s, while the other suctions measured were 95 Pa at the sump, 1 Pa at hole 1, and 5 Pa at hole 2.

3.2 Caulking of Radon Entry Routes

In mid-March, attention was turned to caulking the wall/floor joint and other openings in the slab. The wall/floor joint area was cleaned by a variety of methods. The full procedure involved chipping away all protuberances on the slab or wall which would prevent the caulking nozzle from placing caulk into the wall/floor joint crack; raking out all small pieces of concrete and dirt from the crack; wire brushing the crack area while vacuuming to remove dust and dirt; wiping with a damp sponge and allowing the area to dry. The second procedure was to clean the area with a rotary wire brush mounted in a power-drill, and then vacuum and sponge, and the third procedure was to use a manual wire brush on the area and then vacuum and sponge.

A "sagging" (gun-grade) polyurethane caulk (Dymonic) had been selected for use in this house, but it was reported that a flowable urethane caulk would also work well. A flowable caulk (Vulkem) was ordered, so that both caulks could be compared.

The plumbing stacks had water lines secured to them by duct-tape where they passed through the floor slab. This left an opening through the slab. Each opening was cleaned out and a small dam of Mortite putty placed around the base of the pipe and then filled with Vulkem flowable caulk. The dam was refilled with caulk as the material flowed down the openings.

When the flowable caulk was applied by gun to the wall/floor joint the material stayed on top of the crack for a short while, but within fifteen minutes it disappeared into the crack. Even when the caulk was placed on the wall face above the joint, the material still disappeared down the crack. Even when a second application was made in the same area, the caulk again disappeared down the partially filled crack.

A 'pourable' caulk of higher viscosity than the flowable was also tried, in an effort to reduce the difficulties encountered with the flowable. This pourable caulk was a solvent-based acrylic. However, the pourable caulk was found to behave in a manner similar to the flowable. Moreover, it had a very strong and unacceptable odor, and was found to be objectionable to the workmen and the homeowner even with the use of local exhaust ventilation. Following an owner complaint of the odor being detected upstairs, that night the sump fan was disconnected from the sump and used as a temporary exhaust fan overnight till the solvent had evaporated.

Pressure and smoke testing were conducted with the sump ventilation fan operating in the exhaust and then the pressurization mode. The smoke tests clearly showed that the flowable and pourable caulks had failed to seal the wall/floor joint, but the plumbing stacks were sealed.

The use of the flowable and pourable caulks was abandoned, and application of the sagging urethane caulk started. The next day, Dymonic caulk was applied to the entire wall/floor joint, including the areas where the pourable and flowable caulks had previously been used. To ensure good coverage, a double line of Dymonic was used and spread by tooling to concrete on each side of the previous caulk. The floor-crack at the chimney recess was prepared and caulked with Dymonic by forcing the caulk into the crack with a putty knife, re-caulking and again forcing the caulk into the crack. Radon concentrations measured in the basement were found to range from 2 to 12 pCi/L, averaging 7.3 pCi/L over 66 hours.

The following week the sump was sealed with two layers of Mortite putty under a new sump cover fashioned from lucite and screwed down tightly. Openings for the sump discharge and submerged sump-pump power cord were closed with Mortite gaskets. Eleven sections of the caulk were covered with pieces of polyethylene sheeting taped up the wall and out over the slab to serve as collectors of radon passing through or around the caulk. To achieve good adhesion at the tape strips, concrete dust was removed from the surface by dabbing with Mortite putty.

Two days after installation, the collectors were sampled for radon content. Concentrations ranged from 60 to 300 pCi/L for the eleven collectors covering the wall/floor joint, while results for basement air, a clean-out and a floor crack were 4, 4 and 60 pCi/L. These gave clear evidence of leakage at the areas of caulking. An 'accelerated efflux' test, with a basement exhaust fan running throughout, indicated basement levels ranging from 1 to 12 pCi/L, averaging 5.0 pCi/L over 98 hours.

In early April 1988, the caulk was inspected and tested for adhesion, particularly in those areas where the collectors indicated leakage. Generally the caulk had good attachment to the concrete wall and floor surfaces, even when cut and pulled. Only a few regions of pin-holing could be found, and those were on the wall side of the caulk. As this might have been due to insufficient cleaning of the concrete surface, several sections were cleaned with acetone or paint thinner, and Mortite putty was used to remove surface dust. These areas were then re-caulked with the Dymonic caulk which was tooled into the surface. Collectors were installed over the re-caulked areas.

Inspection of the sump cover showed several regions where the Mortite under the cover was not sealing completely, so the area around the sump was cleaned and collector placed over the sump. The hollow metal house columns were filled with expanding foam, injected through a hole drilled near the bottom of the column to prevent radon entry.

The collectors were sampled two days later and the 11 covering the wall/floor joint were found to contain between 100 and 290 pCi/L , the floor crack 60 pCi/L, the sump cover 580 pCi/L, and clean-out 15 pCi/L, while the basement air contained 10 pCi/L. Radon levels were still high ranging from 5 to 18 pCi/L, and averaging 11.9 pCi/L over 92 hours.

The collectors showed that the elaborate cleaning and re-caulking of the wall/floor joint was not effective in reducing radon leakage. This suggested that the problem was not that the caulk did not adhere to the surface, but rather that there was a porous surface layer on the concrete, which enabled soil gas and associated radon to bypass the caulk. The collector also showed that there was radon leakage at the sump. The cover was removed and the whole area was cleaned and primed with Primer #1 for Dymonic caulk. The top of the crock/slab joint was caulked and, following replacement of the Mortite seal and a broken arm clamp, a sponge rubber seal was added on top. The sump cover was then caulked in place and screwed down to the slab. Another collector test of the sump cover showed little improvement at 430 pCi/L. After this work, basement radon levels ranged from 3 to 12 pCi/L, averaging 7.1 pCi/L over 51 hours.

3.3 Final Installation

As caulking did not provide an acceptable level of sealing against radon entry, a permanent sump ventilation system was installed at the end of May 1988. An 10-cm exit hole was core-drilled through the side basement wall above grade, and an exterior wall-mounted version of the T-2 fan was installed, with a speed controller located beside the power box. A hole was cut in the sump cover to attach a 4 inch exhaust line. The water in the sump had become stagnant, and smelt badly. The owner reported an unacceptable odor in the sump exhaust. This was dealt with by pouring two cups of chlorine bleach down the floor drain connection in the sump lid and flushing that through with a couple of gallons of water.

4 OTHER MEASUREMENTS

The 1987 charcoal canister test gave a radon value of 37.9 pCi/L in the basement. A short-term radon-monitor survey in January 1988 found concentrations in the basement ranged from 12 to 34 pCi/L, averaging 24.4 pCi/L.

Pre-mitigation alpha-track measurements over the period December 1987 to February 1988 gave average radon concentrations of 17.5 pCi/L in the living area and 23.2 pCi/L in the basement.

Post-mitigation alpha-track measurements over the period May to August 1988 gave an average radon concentrations of 2.1 pCi/L in the living area and 4.7 pCi/L in the basement.

The gamma radiation field indoors ranged from 5 to 6 μR/h, averaging 6 μR/h, and the gamma field over the site ranged from 8 to 10 μR/h, averaging 9 μR/h. Fields of 6 to 7 μR/h were found on the concrete front and rear porches.

MEASUREMENTS SUMMARY FOR HOUSE 32

PYLON AB-5 HOURLY MONITORING

MITIGATION SYSTEM	TEST DATE	TEST STATUS	RADON (pCi/L) RANGE	RADON (pCi/L) MEAN	DURATION	FIG.
pre-selection	01/88		12-34	24.4	77 hrs	32-1
sump covered	02/88	before	23-37	31.0	49 hrs	32-2
		after	16-49	29.2	40 hrs	32-2
sump suction	02/88	fan off	22-32	28.6	5 hrs	32-3
		DPmax	0- 2	1.3	43 hrs	32-3
		DPlow	0- 2	1.0	40 hrs	32-3
sump pressured	03/88	maximum blow	1-12	2.9	69 hrs	32-4
		fan off	14-22	18.5	19 hrs	32-4
sump suction	03/88	0.5DPmax	1- 3	1.5	41 hrs	32-5
closure of wall/ floor joint etc.	03/88	Dymonic caulk	2-12	7.3	66 hrs	32-6
improved closure	03/88	new sump cover	1-12	5.0	98 hrs	32-7
improved closure	04/88	more Dymonic	5-18	11.9	92 hrs	32-8
improved closure	04/88	sump caulked; columns foamed	3-12	7.1	51 hrs	32-9

Average pre-mitigation Pylon results (presented in Tables VI, VII and 3):

> Weighted average of Figure 32-1 and the pre-mitigation portion of Figures 32-2 and 32-3 (131 hours total) = 27.0 pCi/L.

Average post-mitigation Pylon results (sump suction with fan at 0.5 DPmax, presented in Tables VI and VII):

> Weighted average of Figure 32-3 (portion at 0.5 DPlow) and Figure 32-5 (81 hours total) = 1.2 pCi/L.

Average post-mitigation Pylon results (slab closure, presented in Table XVI):

> Weighted average of Figures 32-8 and 32-9 (143 hours total) = 10.2 pCi/L.

SYSTEMS MEASUREMENTS

PHASE	MITIGATION SYSTEM	TEST DATE	MEASUREMENTS			COMMENT
			SUCTION (Pa)	FLOW (L/s)	RADON (pCi/L)	
1	pre-selection	01/88			250	sump air
					24	basement air
					96	sewer/slab entry
					25	floor drain
1	sump covered	02/88			900	slab hole 1
			250-500			suction at hole 1
			0			at slab hole 2
					170	hole 2;after suck
1	sump suction	03/88			1	basement air
			180	87	29	at riser; DPmax
			130	76		at riser; DPlow
1	sump pressured	03/88	-110*	87		riser;maximum blow
1	sump suction	03/88	160	76		at riser; DPmax
			1			at hole 1
			5			at hole 2
			95			in sump
			80	58		at riser; 0.5DPmax
			55			in sump
1	closure by caulk	03/88			4	basement air
					90	bag B; wall/floor
					300	bag C; wall/floor
					240	bag D; wall floor
					100	bag E; wall/floor
					60	bag F; floor crack
					90	bag G; wall/floor
					70	bag H; wall/floor
					4	bag I; clean-out
					110	bag J; wall/floor
					75	bag K; wall/floor
					140	bag L; wall/floor
					140	bag M; wall/floor
					150	bag N; wall/floor

(continued)

SYSTEMS MEASUREMENTS (continued)

PHASE	MITIGATION SYSTEM	TEST DATE	MEASUREMENTS			COMMENT
			SUCTION (Pa)	FLOW (L/s)	RADON (pCi/L)	
1	improved caulking	04/88			10	basement air
					580	bag A; sump cover
					150	bag B; wall/floor
					220	bag C; wall/floor
					240	bag D; wall/floor
					130	bag E; wall/floor
					60	bag F; floor crack
					200	bag G; wall/floor
					180	bag H; wall/floor
					15	bag I; clean-out
					100	bag J; wall/floor
					130	bag K; wall/floor
					210	bag L; wall/floor
					120	bag M; wall/floor
					290	bag N; wall/floor
1	sump caulked	04/88			430	bag A; sump cover

* "Negative suction" denotes pressurization relative to house.

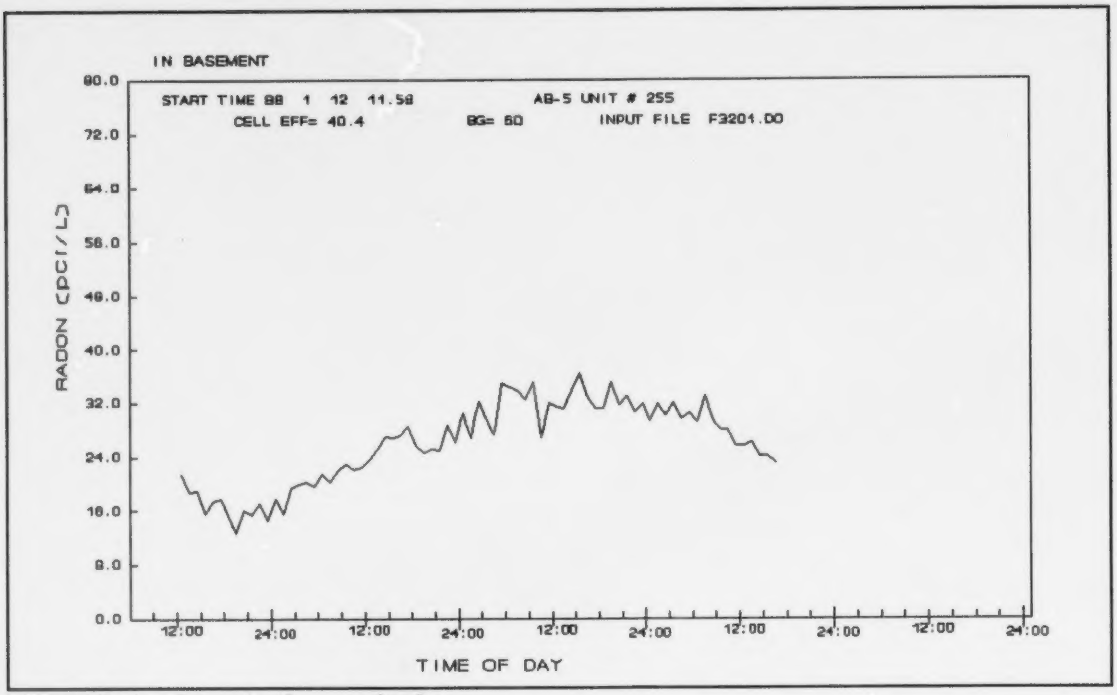


Figure 32-1. Pre-selection monitoring

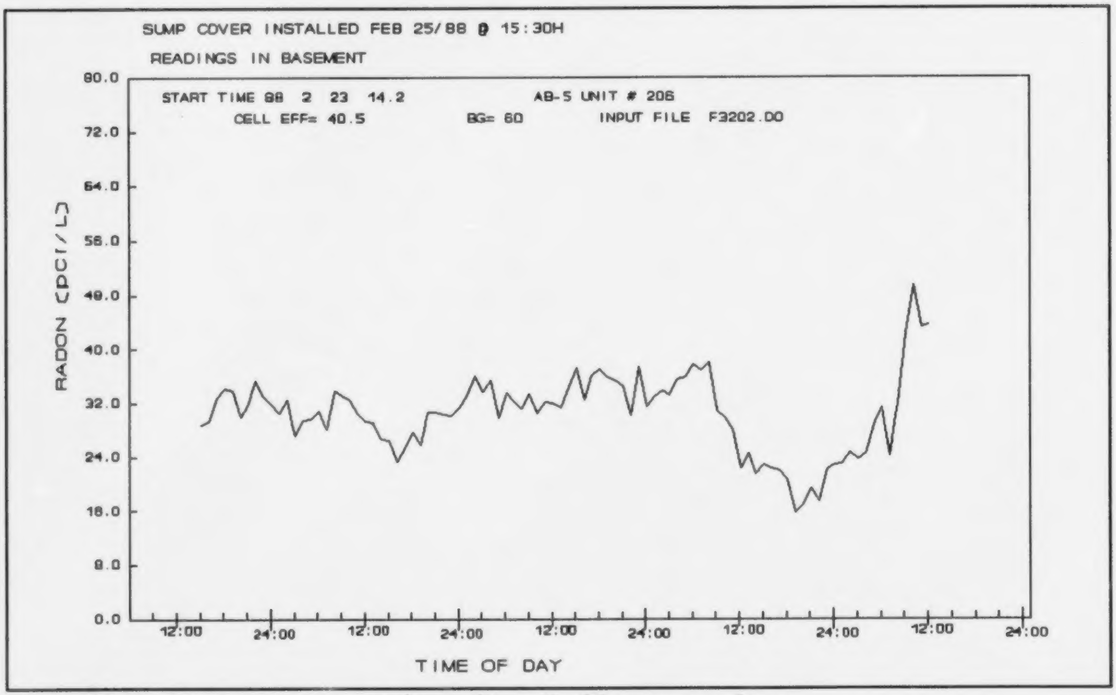


Figure 32-2. Basement concentrations with and without sump closure

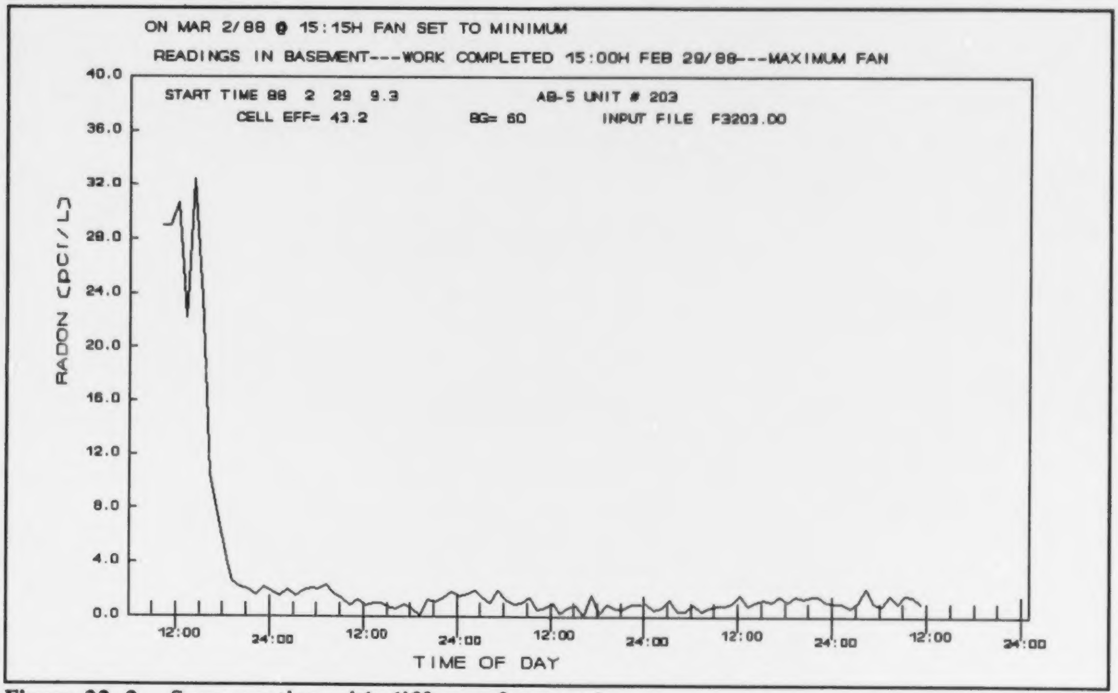


Figure 32-3. Sump suction with different fan speeds

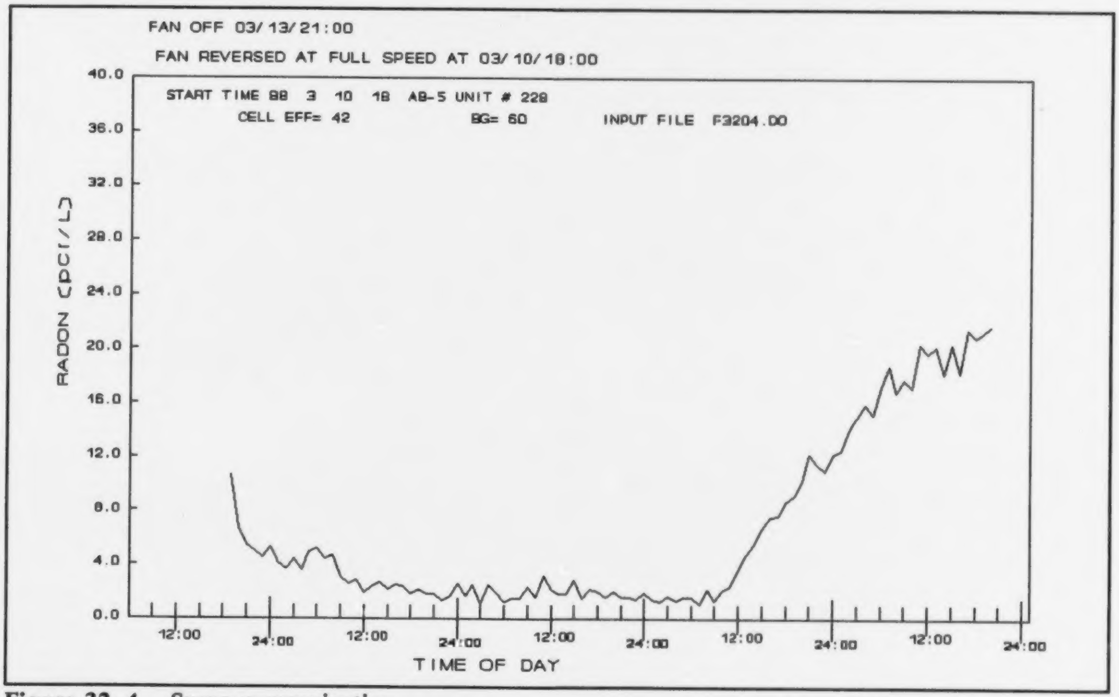


Figure 32-4. Sump pressurization

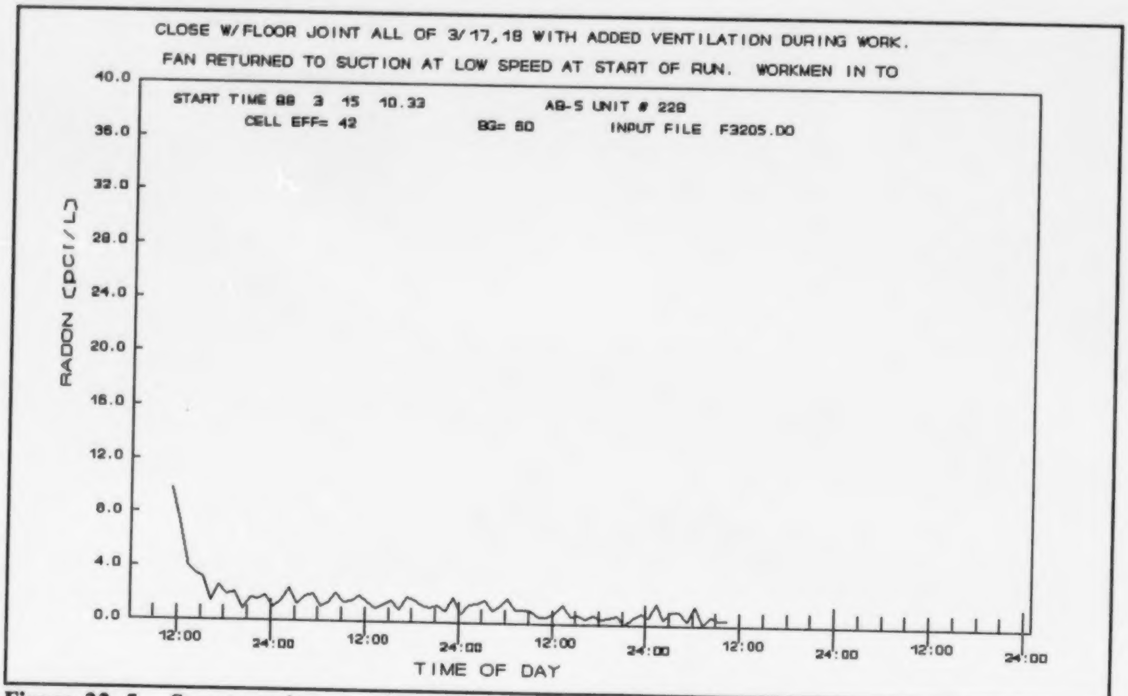


Figure 32-5. Sump suction at reduced fan speed (0.5 DPmax)

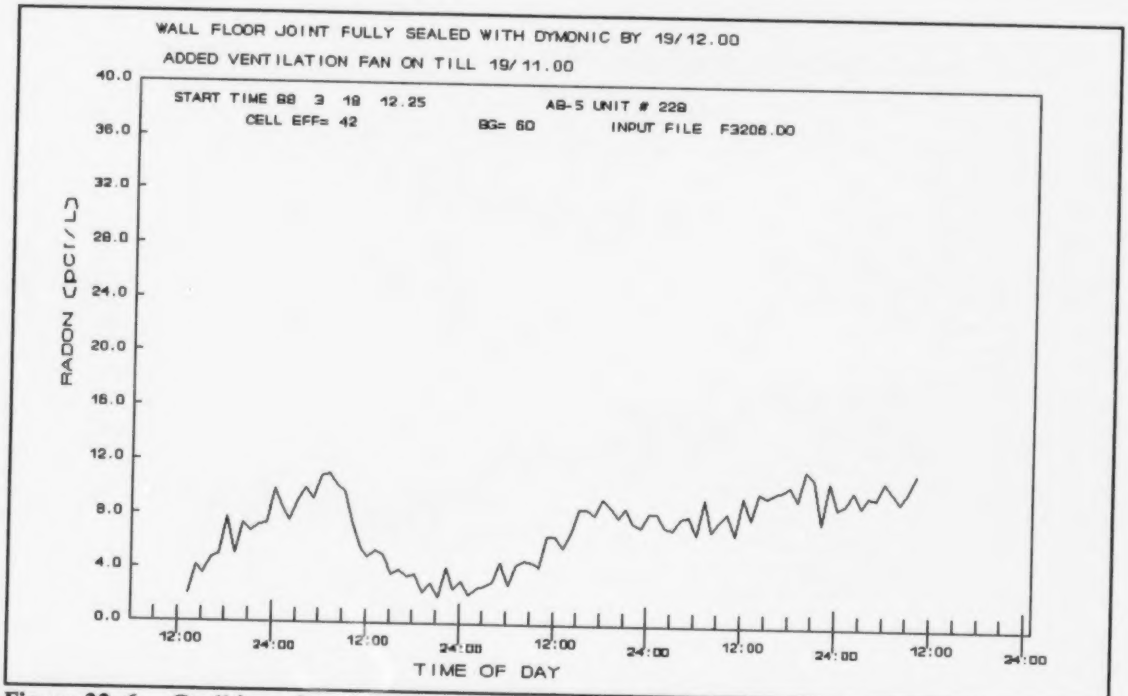


Figure 32-6. Caulking of wall/floor joint and closure of sump

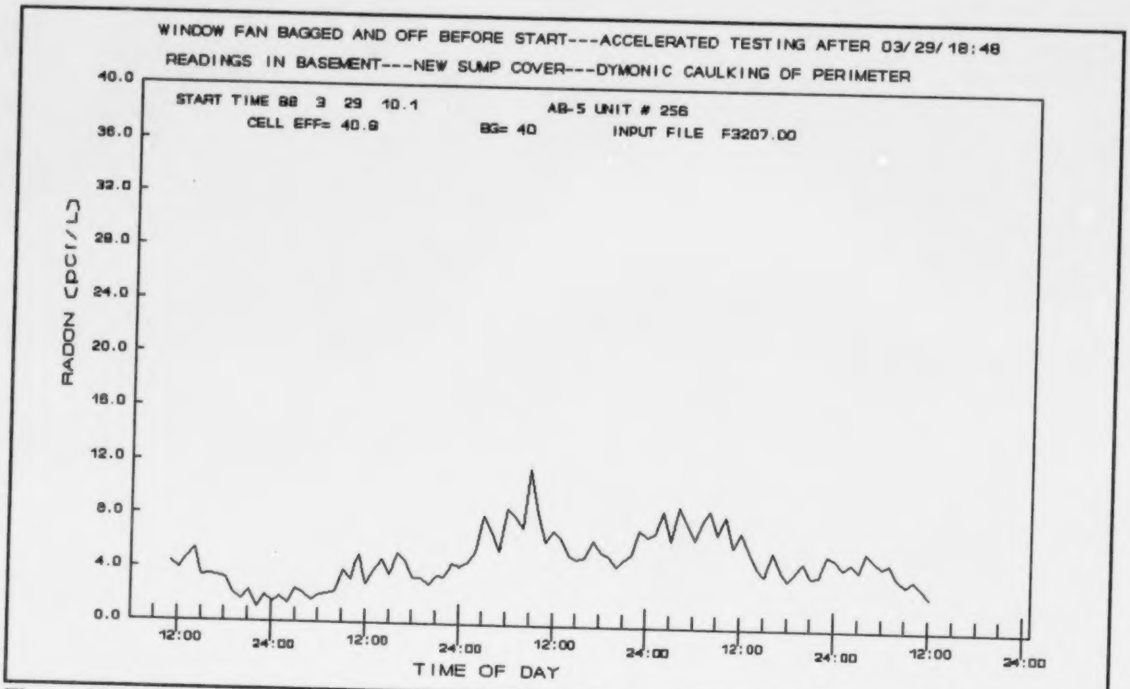


Figure 32-7. Improved closure of wall/floor joint and of sump

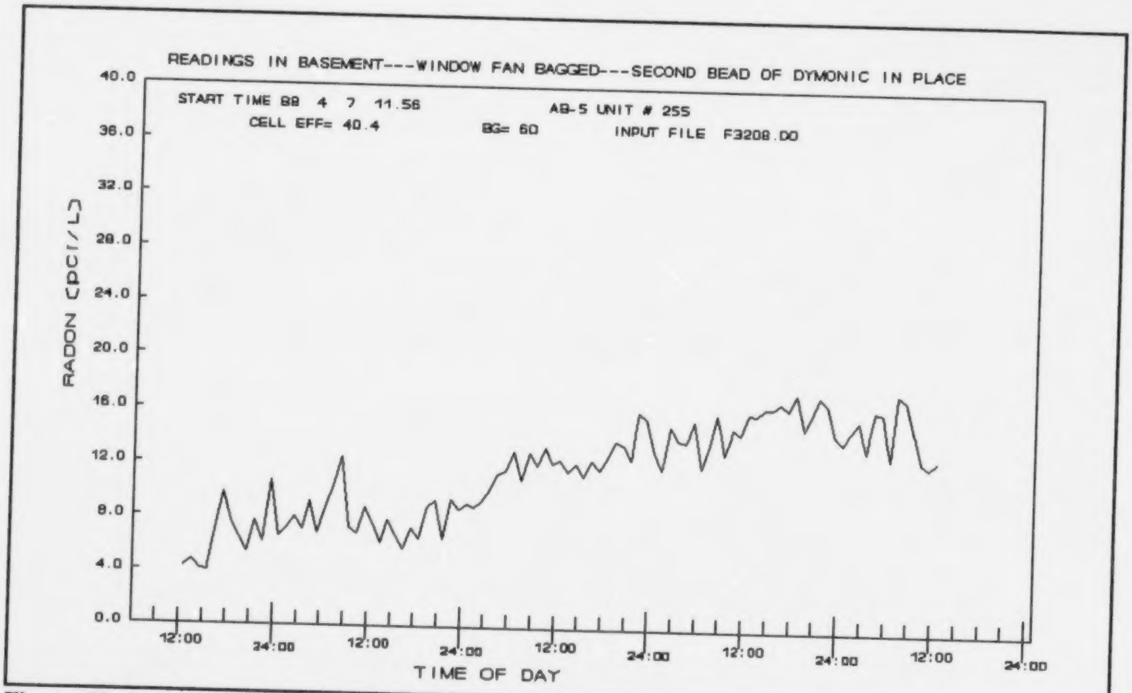


Figure 32-8. Additional effort in caulking wall/floor joint

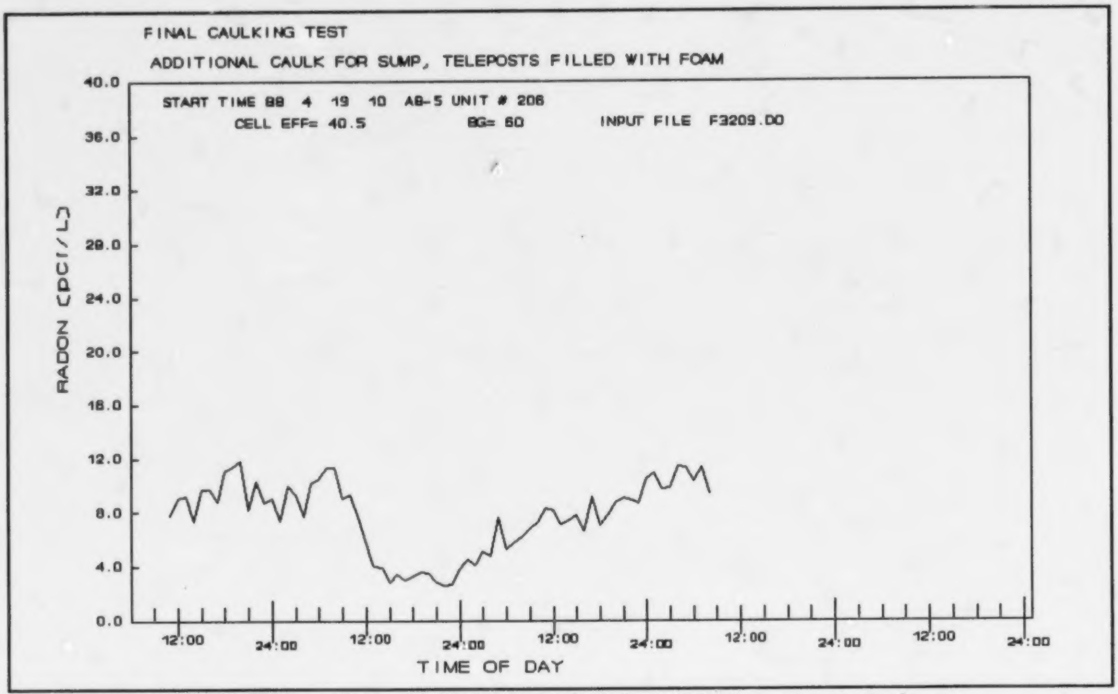
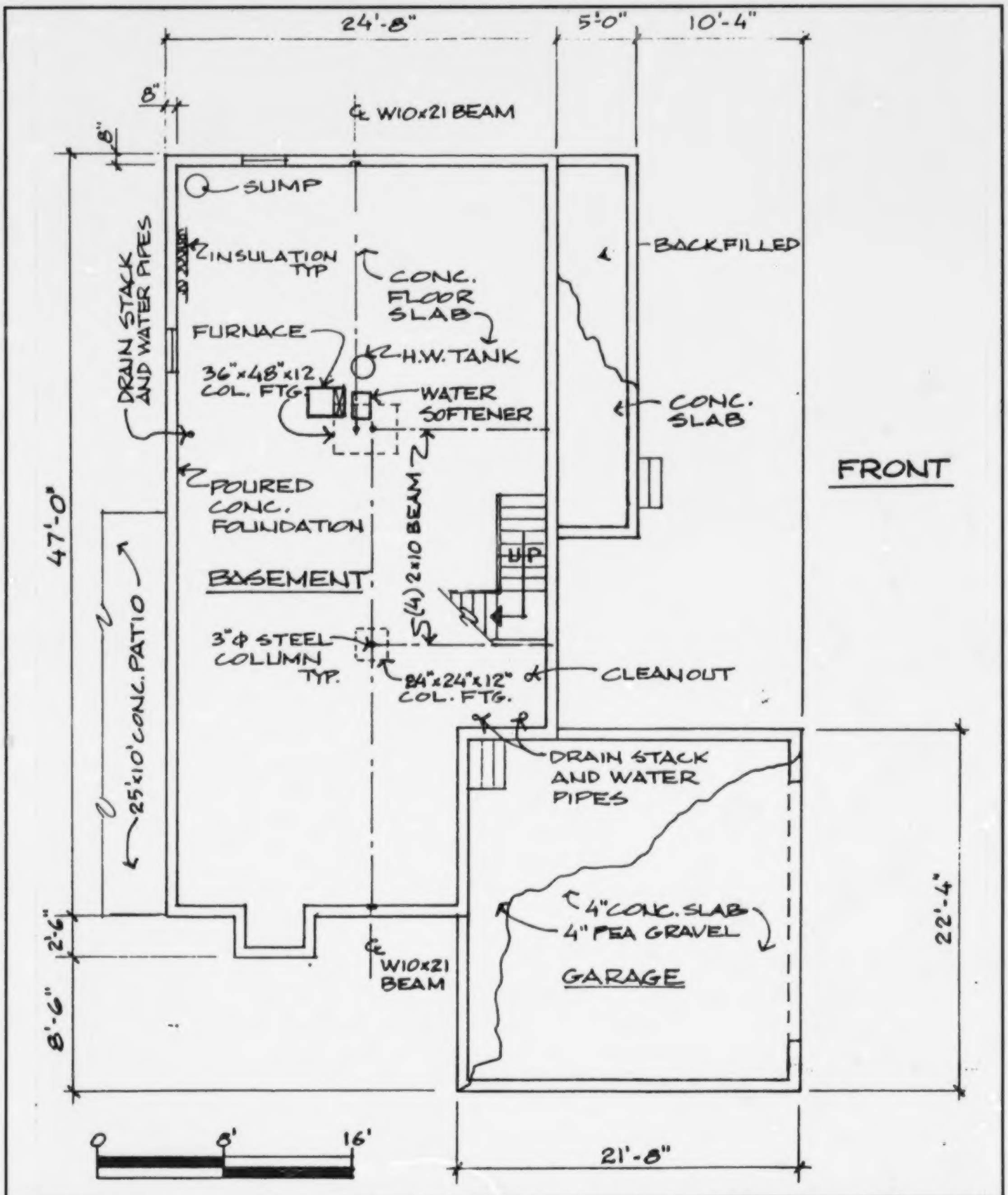
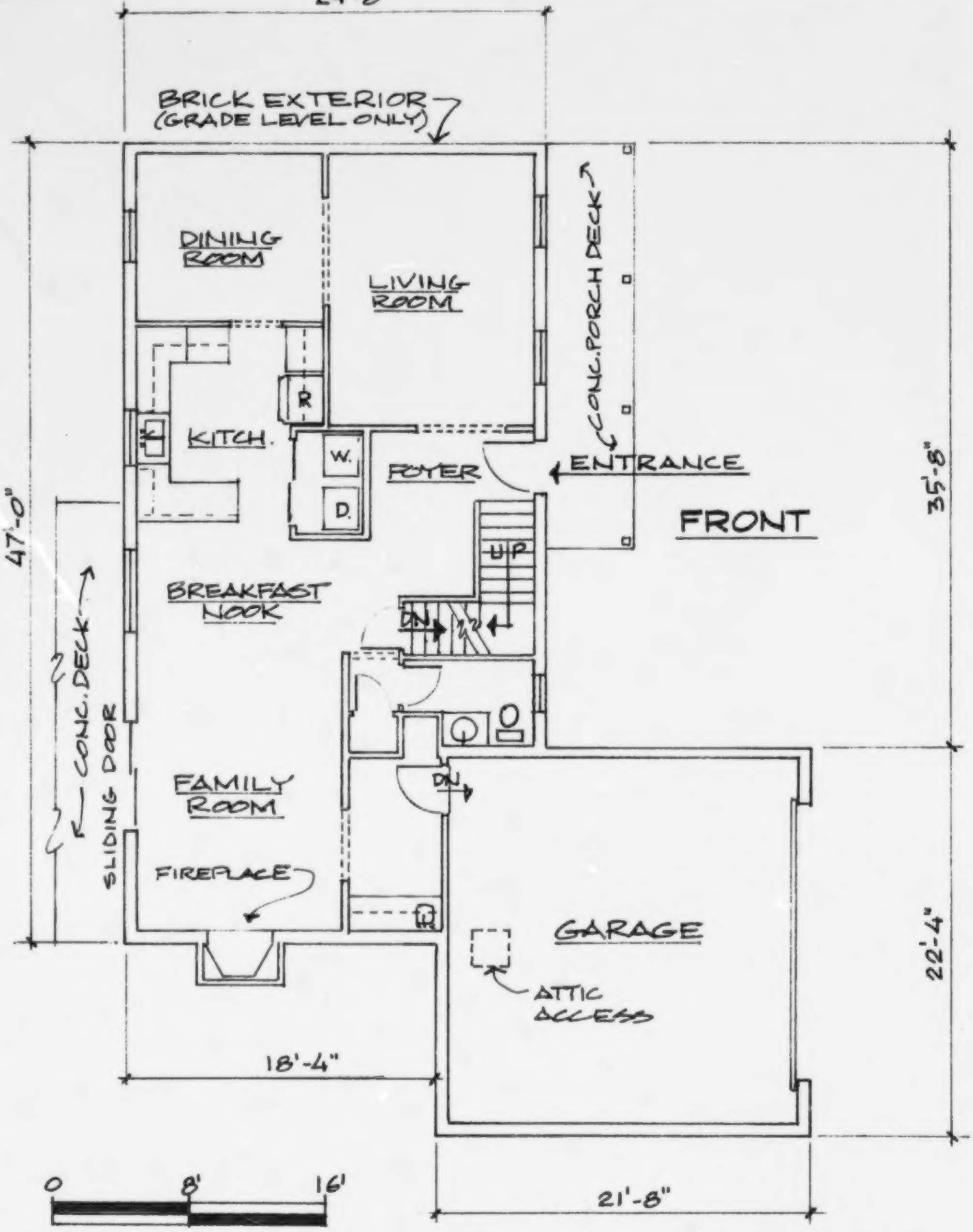


Figure 32-9. Additional caulking around sump, foaming of hollow support columns



ACRES Acres International Corporation	LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
	BASEMENT/FOUNDATION PLAN	Date: 2/23/88	32
	House Group: FULL BASEMENT	PHASE:	



ACRES
Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON

GRADE LEVEL PLAN

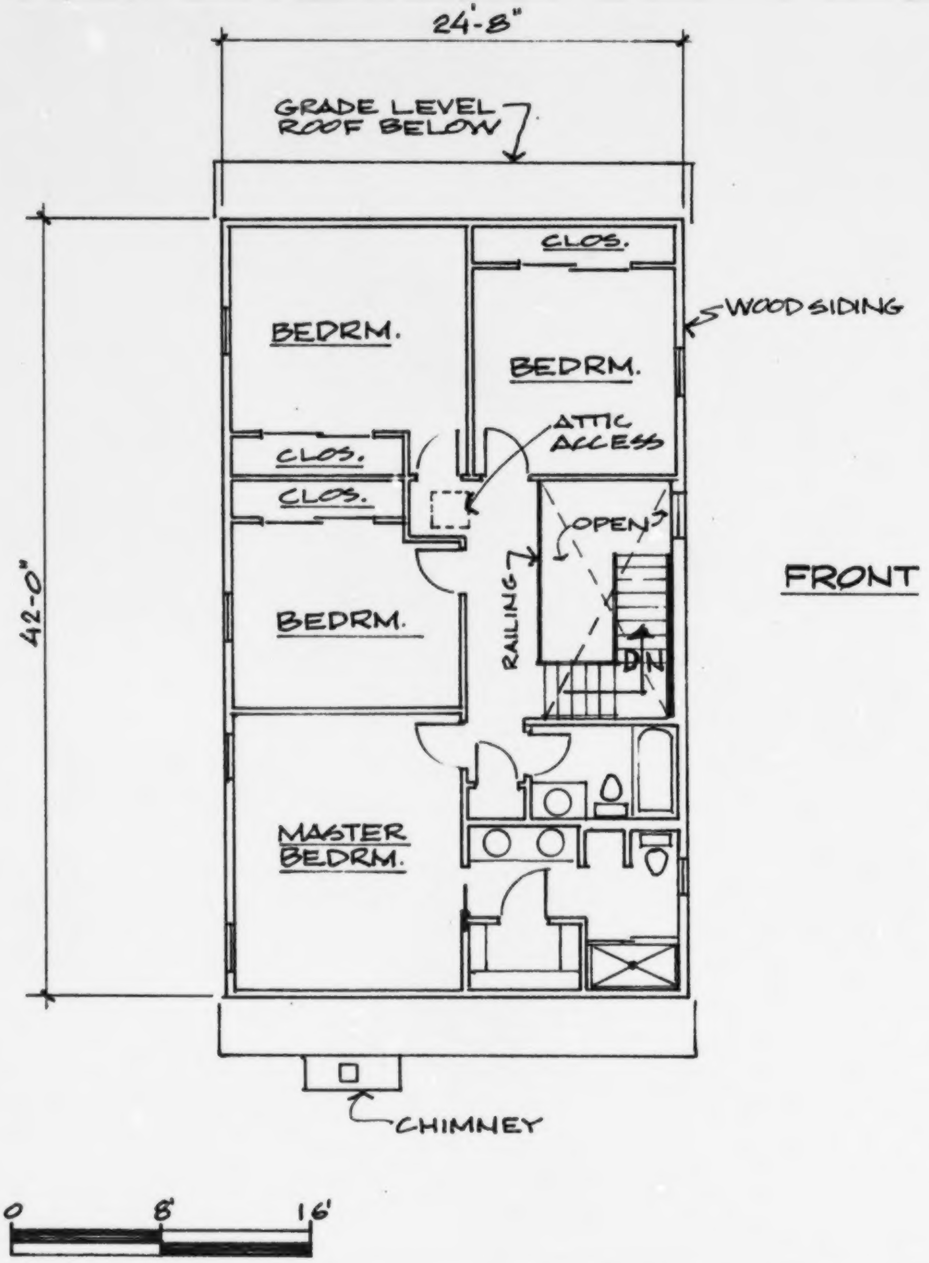
Date: 2/23/88

House Group: **FULL BASEMENT**

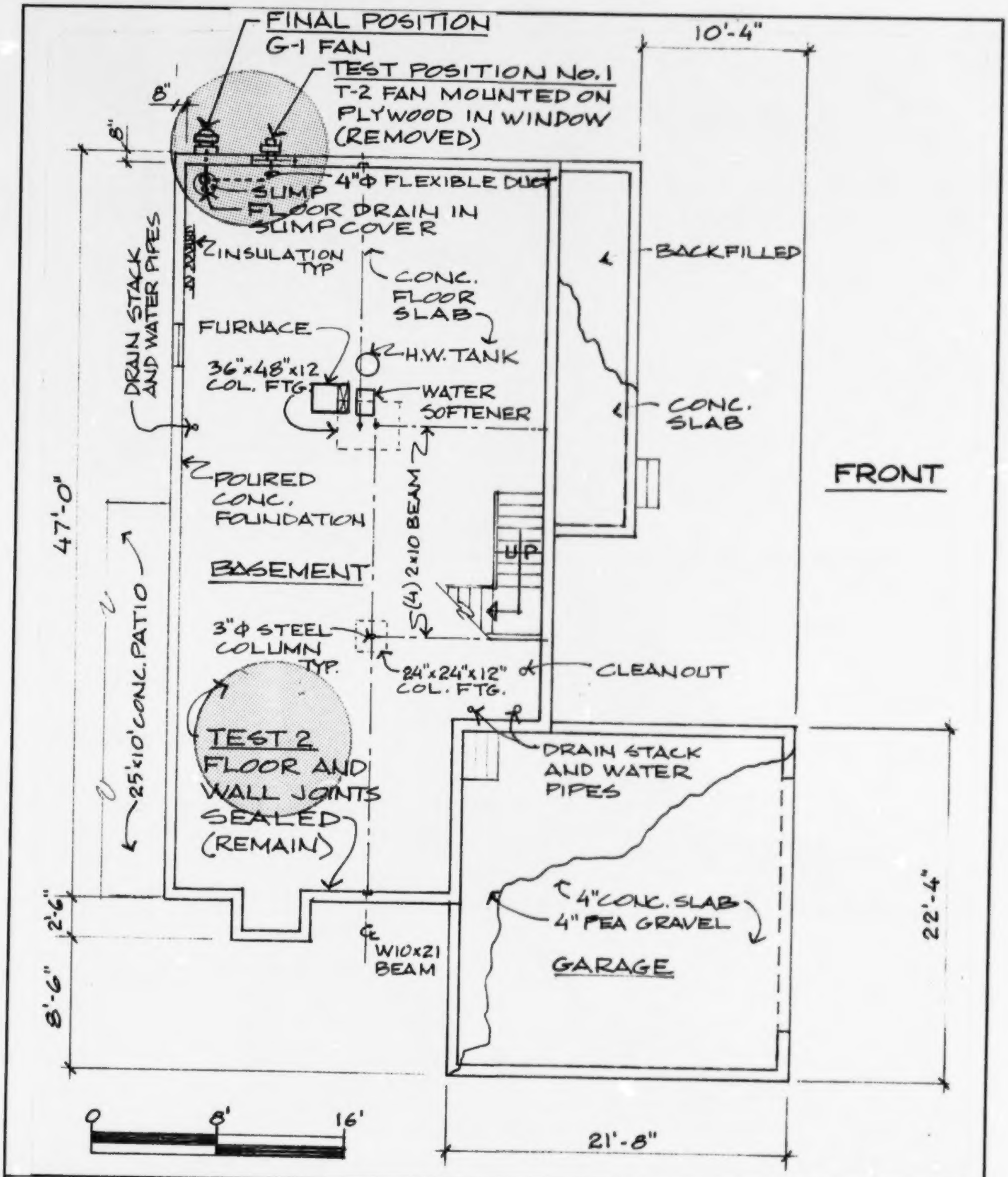
PHASE:

HOUSE NUMBER

32



ACRES Acres International Corporation	LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
	SECOND LEVEL PLAN	Date: 2/23/88	32
	House Group: **FULL BASEMENT**	PHASE:	



LOW COST REDUCTION OF INDOOR RADON

BASEMENT/FOUNDATION PLAN

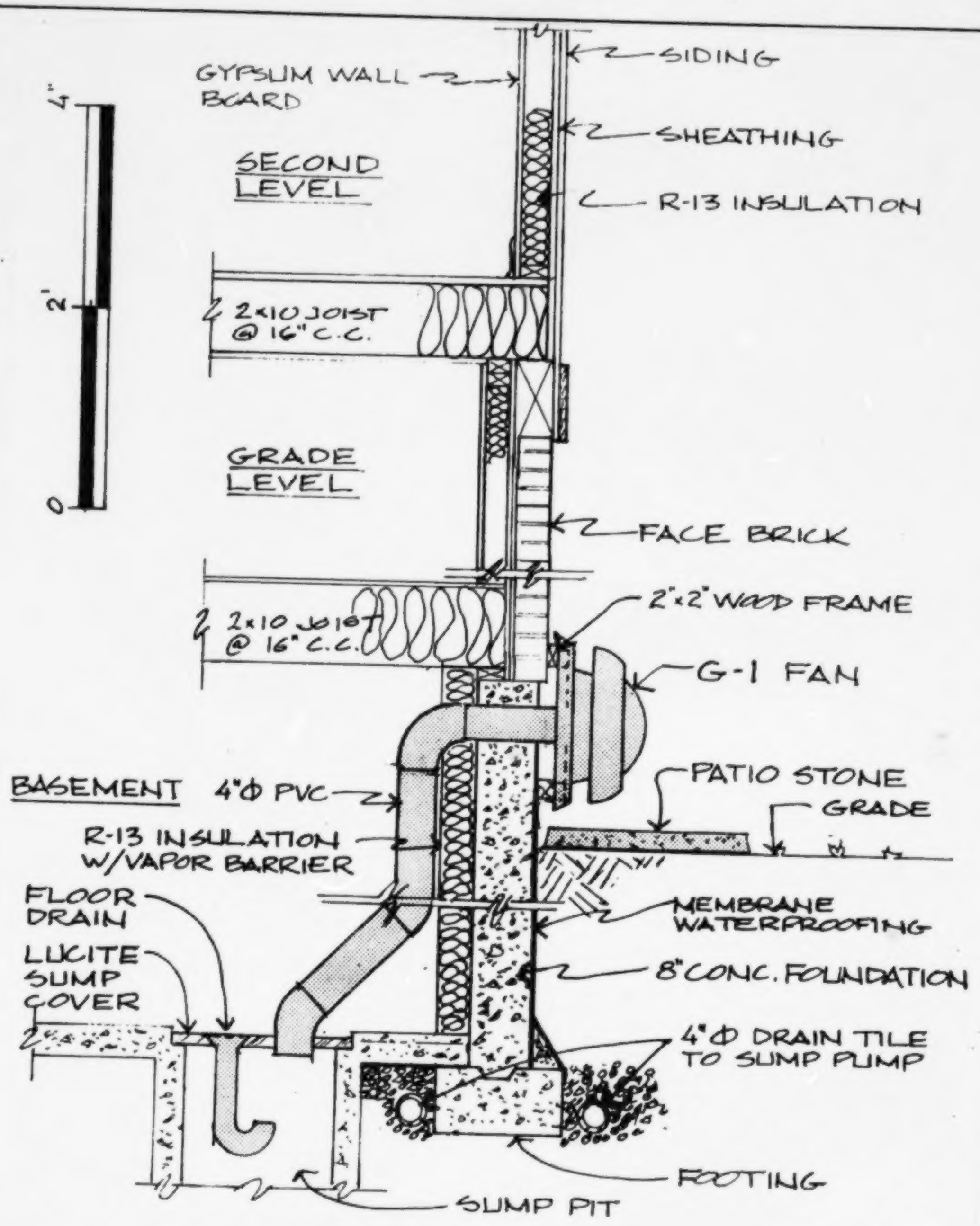
ACRES
Acres International Corporation

Mitigation system: SUMP SUCTION

Date: MAY 1988

PHASE: TESTS AND FINAL

HOUSE NUMBER 32



ACRES
Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON

HOUSE NUMBER 32

SECTIONS/DETAILS

Date: MAY 1988

Mitigation system: SUMP SUCTION

PHASE:FINAL

HOUSE 33

1 GENERAL DESCRIPTION

This small (120 m^2) single-story crawl-space house with attached garage was built in the mid 1960's in a suburban subdivision in southeast Fairborn. The foundation walls are of hollow concrete block, topped with a cap block, and the exterior wall finish is brick. Entry to the crawl space is by a trap door in a hall closet. The crawl-space floor is covered with pea gravel. The five 40 by 20 cm foundation ventilation openings are above grade and are closed in winter by internal flaps. There is no insulation between the joists supporting the overhead wooden floor. This floor is mainly covered with wall-to-wall carpeting except for the vestibule, kitchen and the bathrooms, which are covered with vinyl sheet and tiles respectively. Water is obtained from a well via a pressure storage tank located in the crawl space. Heating and air conditioning is by a downflow forced-air furnace with metal ducts running along the crawl-space ceiling and air returns down the interior of walls. Connections between the crawl space and the living area include the entry from the closet, the duct network, and openings around the sewer and water pipes.

2 INVESTIGATION

In January 1988, a short-term continuous radon-monitor measurement made as part of the pre-selection process found that, over 15 hours, concentrations in the crawl space ranged from 22 to 33 pCi/L, averaging 26.3 pCi/L, while concentrations in the living room ranged from 10 to 14 pCi/L, averaging 11.5 pCi/L over 27 hours.

At the end of March 1988, a test hole was drilled at the rear of the house to a depth of 2 m with a power auger. The top 30 cm was an organic soil, underlain by about 60 cm of a fine grained clay. Beneath this was about 60 cm of a coarser grained clay, and at the bottom of the hole there was wet sandy clay. A 4-inch pipe was inserted into the hole to keep it open. Grab sampling on two separate days, a few days later, showed radon levels in the pipe to be 69 and 60 pCi/L.

At that time preparations were made for the crawl space to be ventilated on a temporary basis. A plywood panel was cut to fit into a ventilation opening, and a flange was mounted on the plywood; flexible (clothes dryer) ducting was to be connected to the flange, to serve as the exhaust for a T-2 fan mounted in a box in the crawl space.

In April 1988, further radon monitoring was conducted with the crawl-space vents closed (considered the pre-mitigation condition). Over an 89-hour period, levels in the crawl space ranged from 26 to 60 pCi/L, averaging 43.9 pCi/L, while concentrations in the living room ranged from 1 to 28 pCi/L, averaging 18.2 pCi/L.

Simultaneous perfluorocarbon tracer (PFT) studies were also conducted with the vents closed to measure ventilation and transfer rates. The ventilation rate for the living space was 0.35 ac/h while that for the crawl space was 0.30 ac/h. The measured ratio of living-area concentration to crawl-space concentration for a tracer released in the crawl space is, at 0.28 (8.2/29.7), a little lower than the measured radon ratio of 0.41 (18/44). Perhaps this can be attributed to poor mixing of the tracer in the crawl space, leading to detection of overly high concentrations by the nearby collector.

When the vents were opened to provide natural crawl-space ventilation, radon levels in the crawl space ranged from 1 to 7 pCi/L, averaging 3.8 pCi/L (Figure 33-8), while upstairs levels ranged from 0 to 6 pCi/L, averaging 2.9 pCi/L (Figure 33-7), over a 98-hour period. Thus, crawlspace radon had been reduced by 92% and living-space radon was reduced by 84%. Levels in the living area were 78% of the crawl-space levels on average.

With the vents open, PFT measurements indicated a large increase in crawl-space ventilation rate from 0.30 to 1.56 ac/h and a smaller increase from 0.35 to 0.58 ac/h for the living area. These results seem reasonable but, once again, the tracer concentration ratio of 0.36 is somewhat lower than the measured radon ratio of 0.78.

The vents were then closed and a temporary fan, providing a flow rate of 57 L/s at a maximum suction of 200 Pa, was installed to exhaust the crawl space. Over a 93-hour period, radon levels in the crawl space ranged from 15 to 34 pCi/L, averaging 21.9 pCi/L (Figure 33-6), while levels in the living area ranged from 0 to 4 pCi/L, averaging 1.3 pCi/L (Figure 33-5). Thus, the lowest living-area results occurred with crawl-space concentrations approaching pre-mitigation levels. Although the fan is inducing radon to leave the soil, it is also dispersing it to the outdoors before it can seep into the living space. Grab sampling showed radon levels in the ground riser were now reduced to 13 pCi/L.

PFT studies conducted under these conditions indicated an increase in the living-area ventilation rate at 0.50 ac/h, compared with 0.35 ac/h without the fan. However, with the fan turned on the crawl-space ventilation rate increased only from 0.30 to 0.39 ac/h. Also, the tracer concentration ratio and the radon ratio are practically identical at 0.06.

In late May 1988, a T-2 in-line centrifugal fan was permanently installed inside the rear vent chosen by the owner and a fan-speed controller was mounted in a box installed by the electrician on a separate line to the fuse box.

3 OTHER MEASUREMENTS

The 1987 charcoal canister test gave a radon value of 18.2 pCi/L in the living room. A short-term continuous radon-monitor survey in January 1988 found concentrations in the living room ranged from 10 to 14 pCi/L, averaging 11.5 pCi/L, while concentrations in the crawl space ranged from 22 to 33 pCi/L, averaging 26.3 pCi/L.

Pre-mitigation alpha-track measurements with the crawl-space vents closed over the period December 1987 to February 1988 gave average radon concentrations of 8.4 pCi/L in the living area and 17.6 pCi/L in the crawl space.

Alpha-track measurements during the period May to August 1988 — with the crawl space vents open and with the exhaust fan off — gave average radon concentrations of 2.9 pCi/L in the living area, and 7.3 pCi/L in the crawl space.

The gamma radiation field in the house ranged from 4 to 7 μR/h, averaging 5 μR/h, whereas the gamma field over the site ranged from 5 to 10 μR/h, averaging 7 μR/h.

MEASUREMENTS SUMMARY FOR HOUSE 33

PYLON AB-5 HOURLY MONITORING

MITIGATION SYSTEM	TEST DATE	TEST STATUS	RADON (pCi/L) RANGE	MEAN	DURATION/ LOCATION	FIG.
pre-selection	01/88		22-33	26.3	15 hrs; CS*	33-2
			10-14	11.5	27 hrs; LR*	33-1
pre-mitigation	04/88	vents closed	26-60	43.9	89 hrs; CS	33-4
		vents closed	9-28	18.2	89 hrs; LR	33-3
crawl-space exhaust	04/88	fan on;DPmax	15-34	21.9	93 hrs; CS	33-6
		fan on;DPmax (vents closed)	0- 4	1.3	93 hrs; LR	33-5
natural crawl-space ventilation	04/88	vents open	1- 7	3.8	98 hrs; CS	33-8
		vents open	0- 6	2.9	98 hrs; LR	33-7

* CS=Crawl Space; LR=Living Room

Average pre-mitigation Pylon results (presented in Tables XII, XIII and 3):

Living area
Weighted average of Figures 33-1 and 33-3 (116 hours total) = 16.6 pCi/L.

Crawl space
Weighted average of Figures 33-2 and 33-4 (104 hours total) = 41.3 pCi/L.

Average post-mitigation Pylon results:

Living area
natural crawl-space ventilation (Table XII) — Figure 33-7 (98 hr) = 2.9 pCi/L.
forced crawl-space exhaust (Table XIII) — Figure 33-5 (93 hr) = 1.3 pCi/L.

Crawl space
natural crawl-space ventilation (Table XII) — Figure 33-8 (98 hr) = 3.8 pCi/L.
forced crawl-space exhaust (Table XIII) — Figure 33-6 (93 hr) = 21.9 pCi/L.

SYSTEMS MEASUREMENTS

PHASE	MITIGATION SYSTEM	TEST DATE	MEASUREMENTS			COMMENT
			SUCTION (Pa)	FLOW (L/s)	RADON (pCi/L)	
1	pre-mitigation (4" pipe augured into ground)	03/88			69	ground riser
					60	ground riser
1	crawl-space exhaust	04/88		44		flexiduct outlet
			-200*	50		at fan (exhaust side)
					13	ground riser

* "Negative suction" denotes pressurization.

PFT VENTILATION STUDIES

TEST DATE	CRAWL-SPACE CONDITIONS	VENTILATION RATES				CONCENTRATION RATIO (LIVING/CRAWL)
		LIVING AREA		CRAWL SPACE		
		(m^3/h)	(ac/h)	(m^3/h)	(ac/h)	
4/88	vents closed	104	0.35	43	0.30	8.2/29.7
4/88	vents open	173	0.58	221	1.56	2.0/5.6
4/88	exhaust on	149	0.50	55	0.39	1.3/22.6

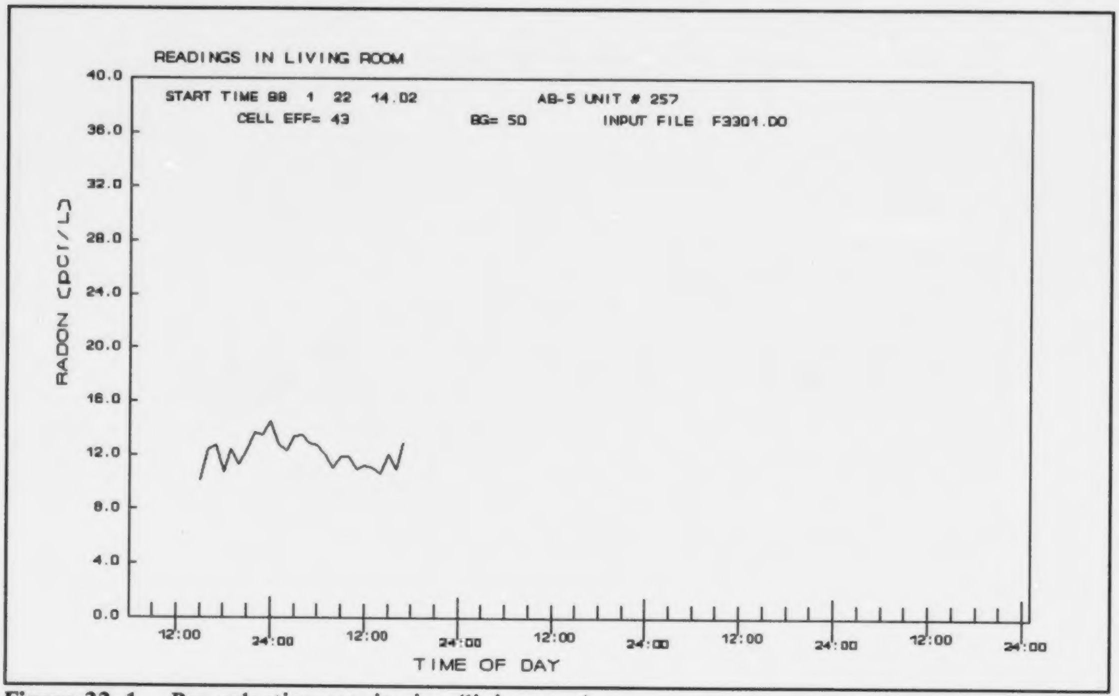


Figure 33-1. Pre-selection monitoring (living area)

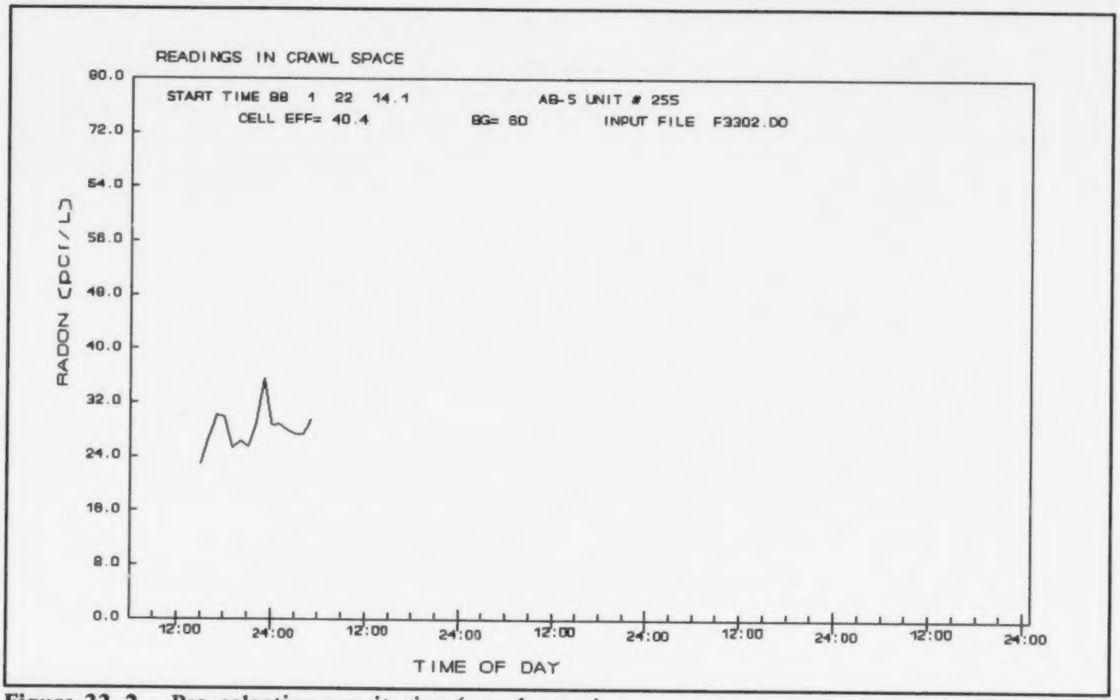


Figure 33-2. Pre-selection monitoring (crawl space)

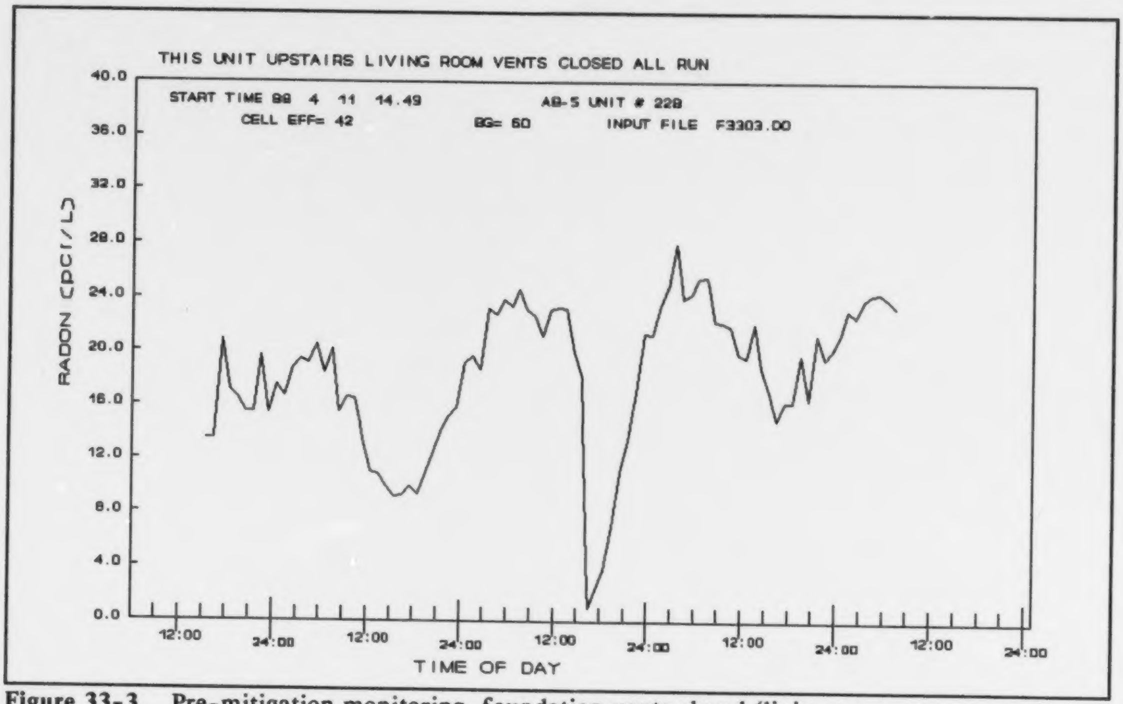


Figure 33-3. Pre-mitigation monitoring, foundation vents closed (living area measurement)

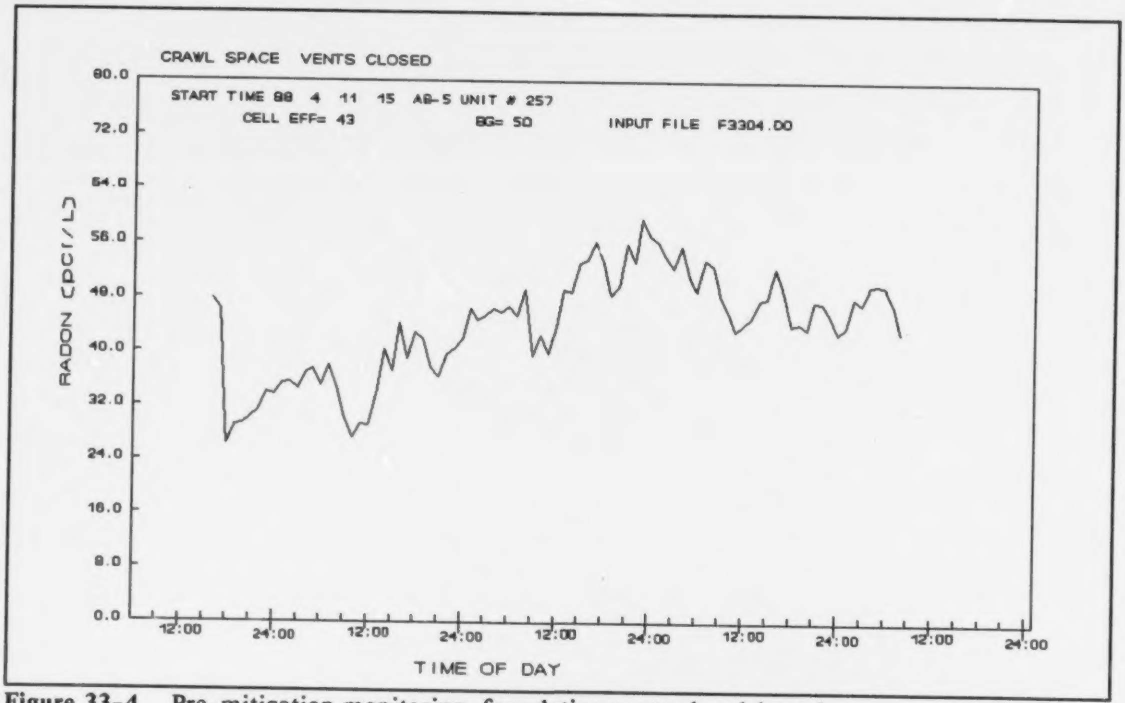


Figure 33-4. Pre-mitigation monitoring, foundation vents closed (crawl space measurement)

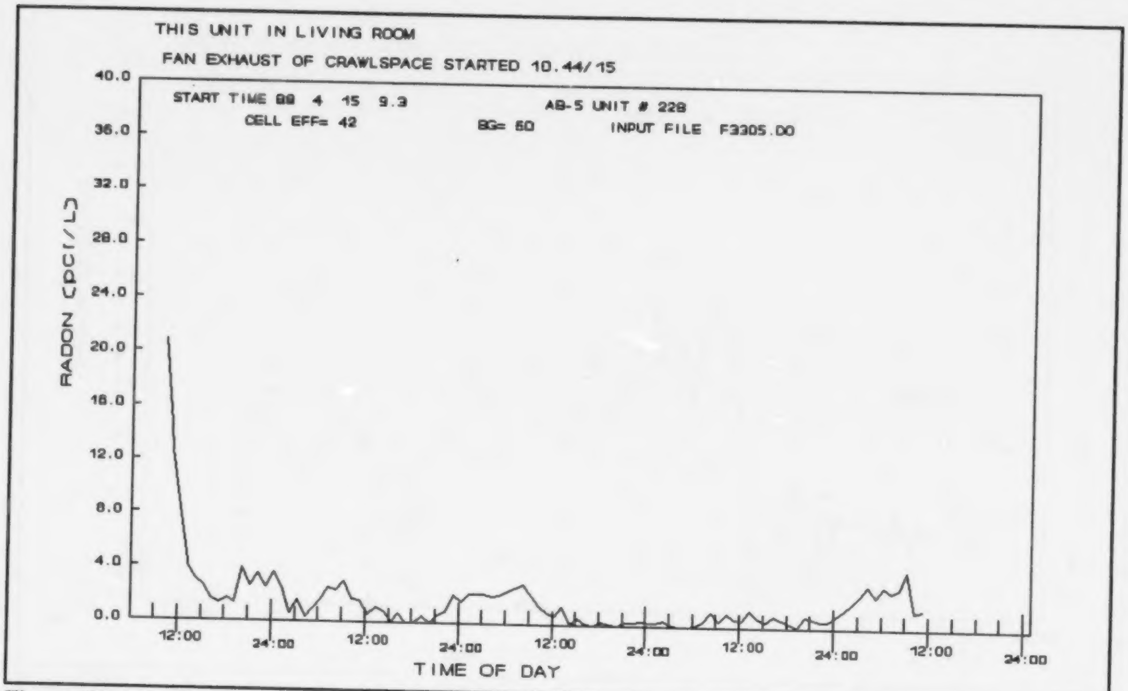


Figure 33-5. Forced crawl-space exhaust (living area measurement)

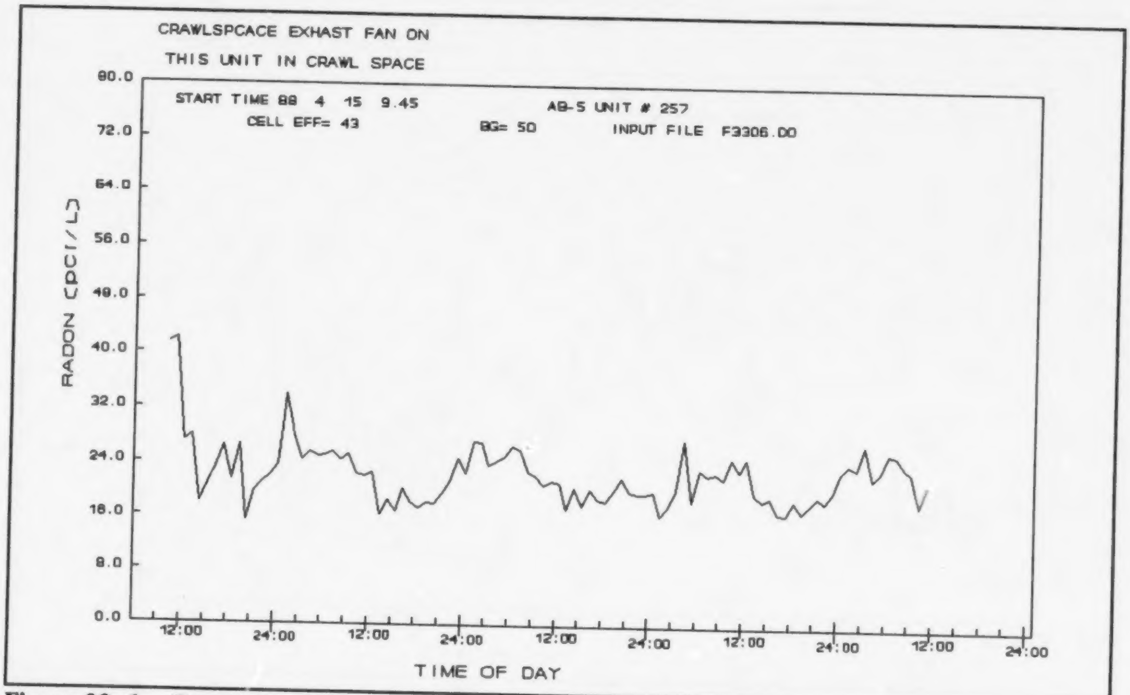


Figure 33-6. Forced crawl-space exhaust (crawl-space measurement)

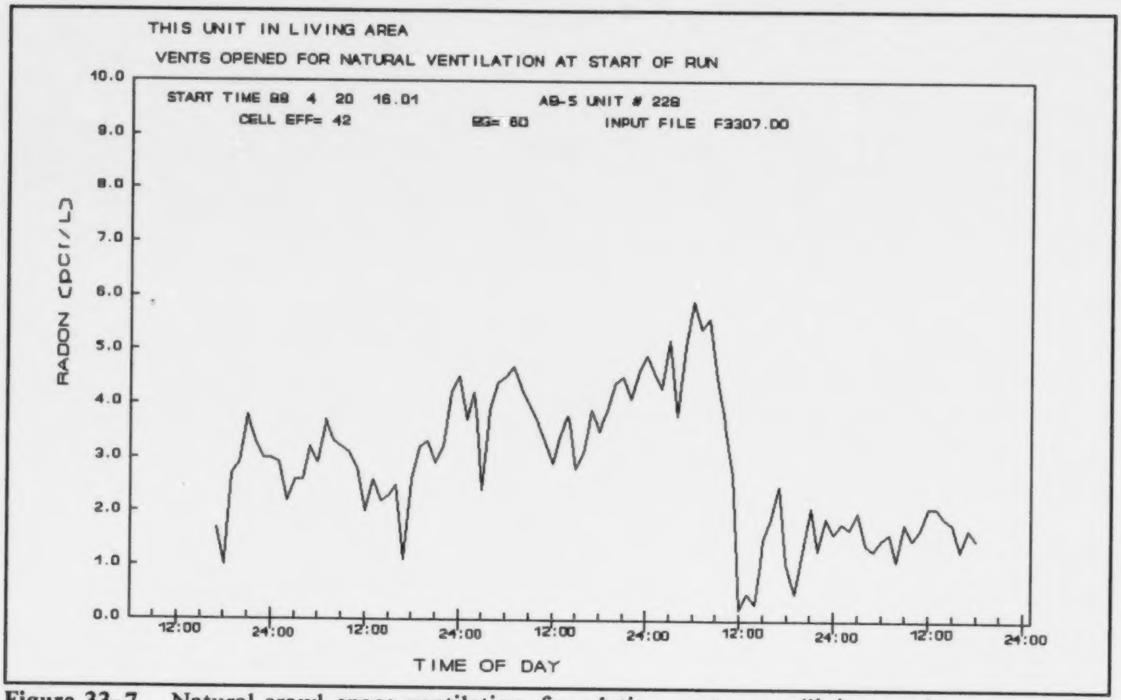


Figure 33-7. Natural crawl-space ventilation, foundation vents open (living area)

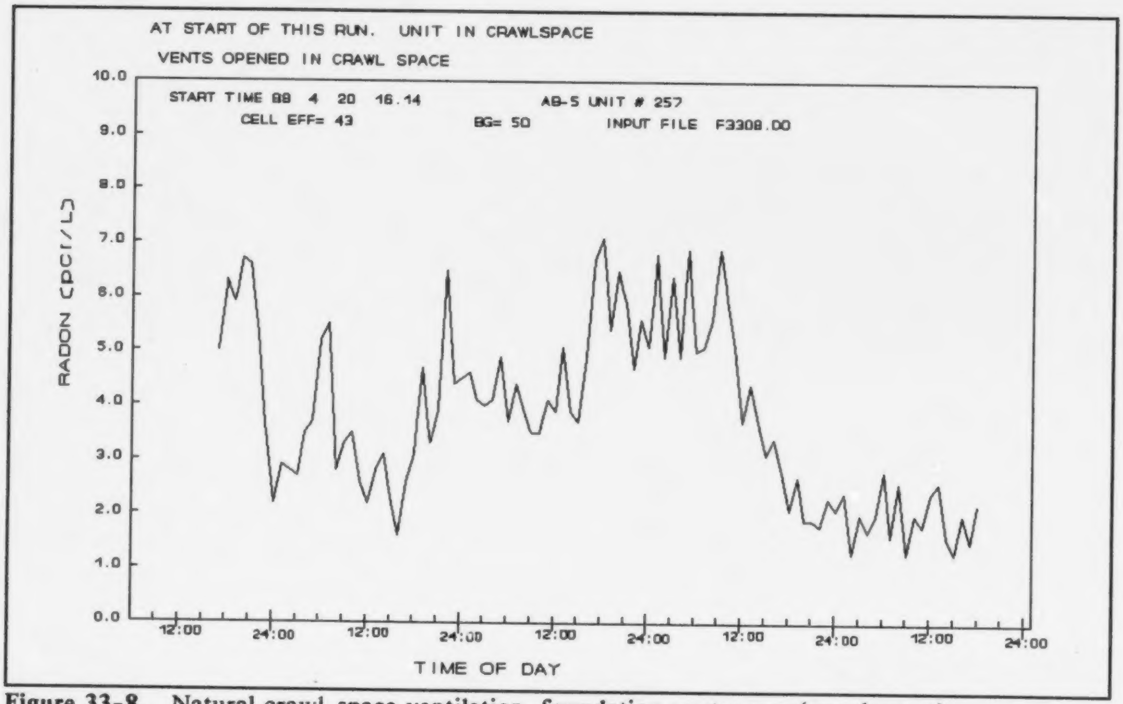
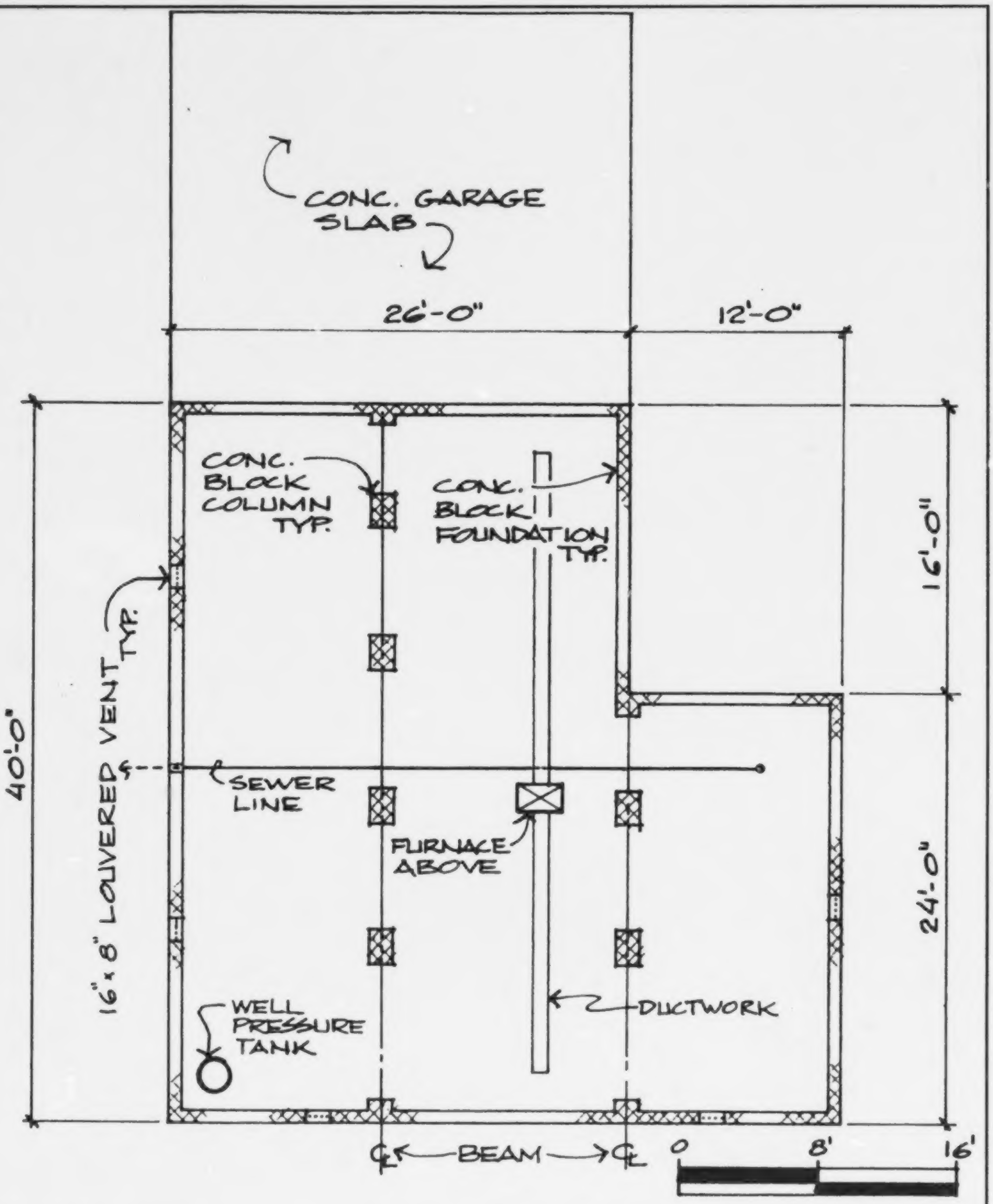


Figure 33-8. Natural crawl-space ventilation, foundation vents open (crawl space)



ACRES
Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON

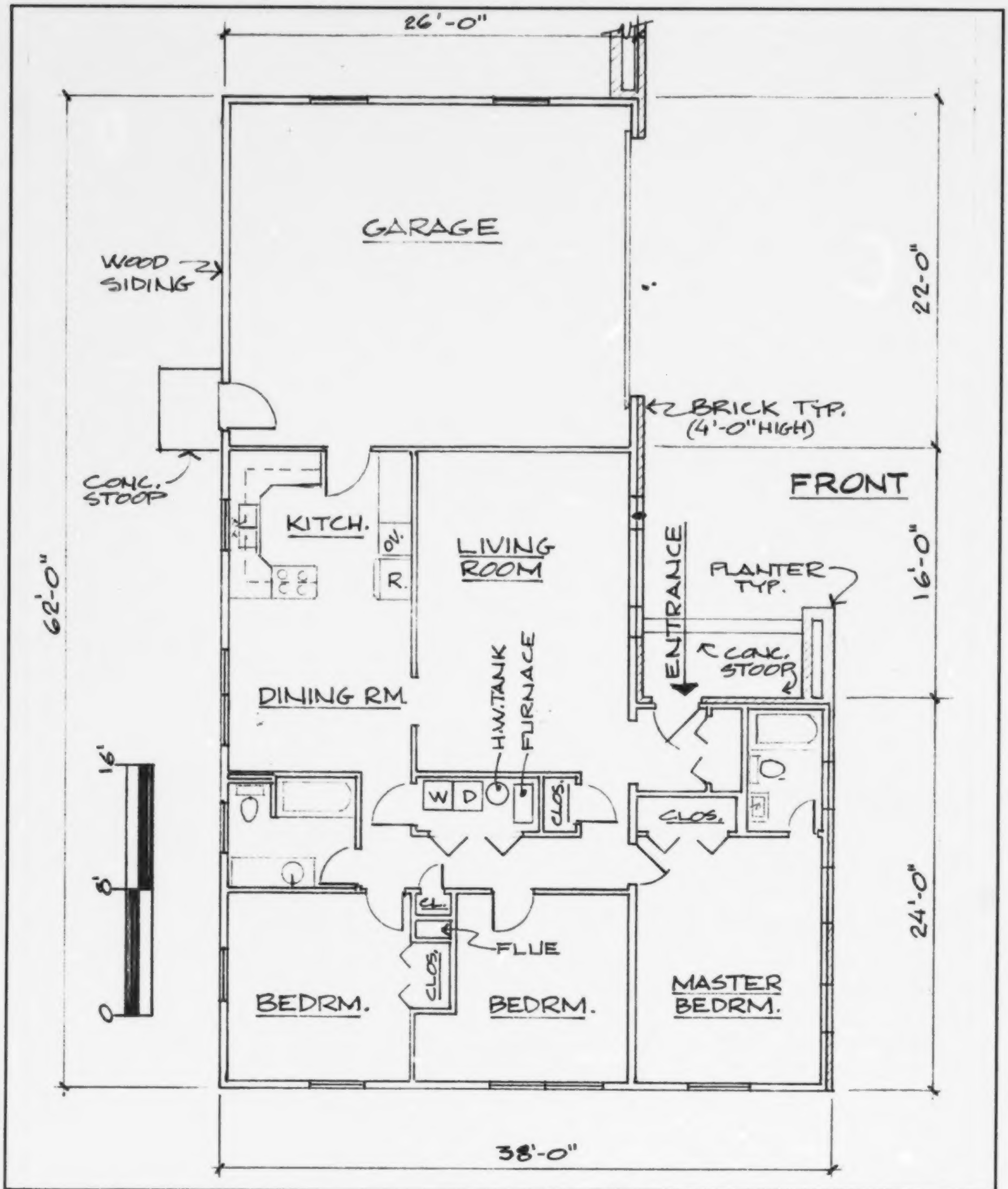
HOUSE NUMBER 33

CRAWL SPACE

Date: 2/26/88

House Group: CRAWL SPACE

PHASE:



ACRES
Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON

GRADE LEVEL PLAN

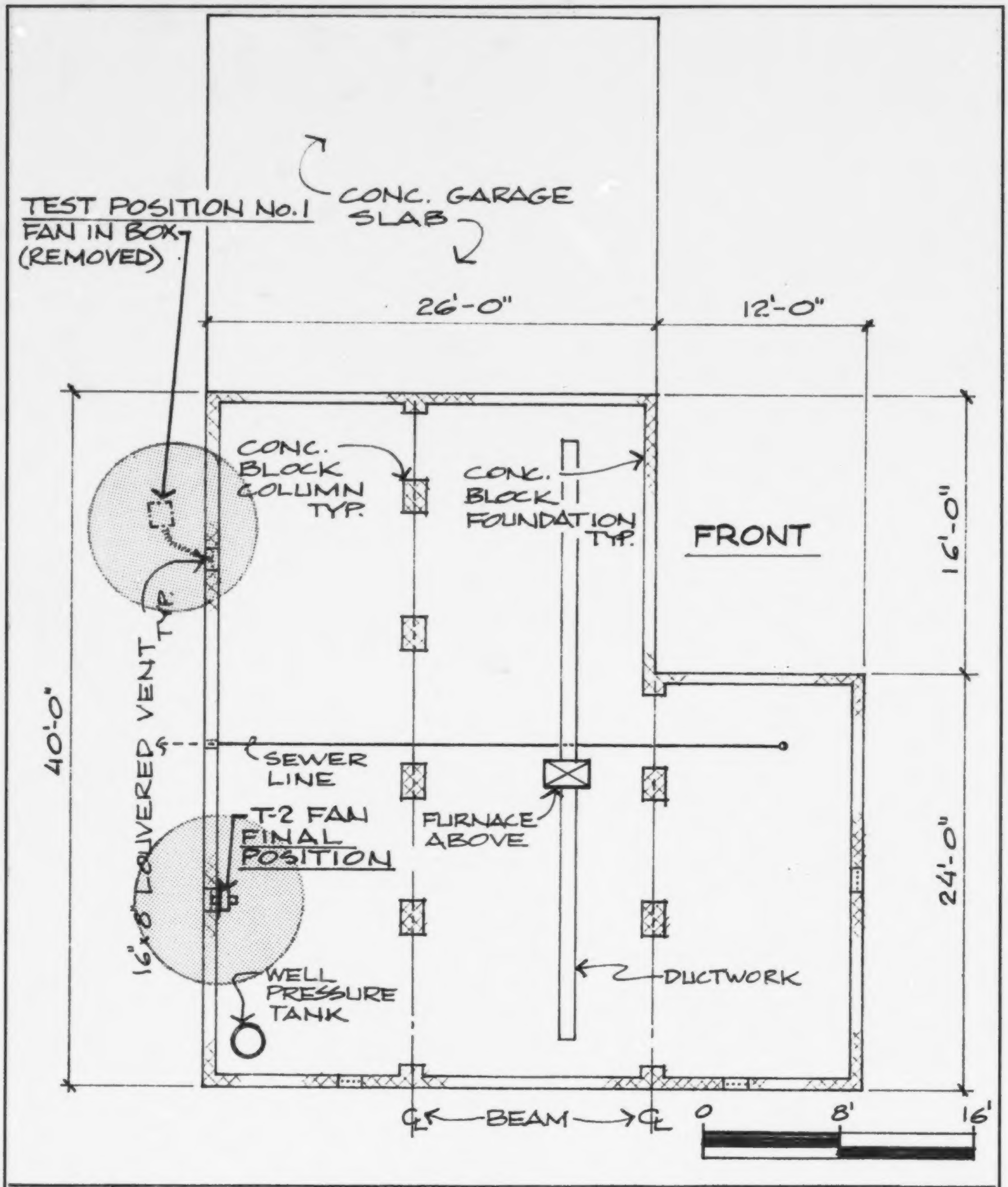
Date: 2/24/88

House Group: **CRAWL SPACE**

PHASE:

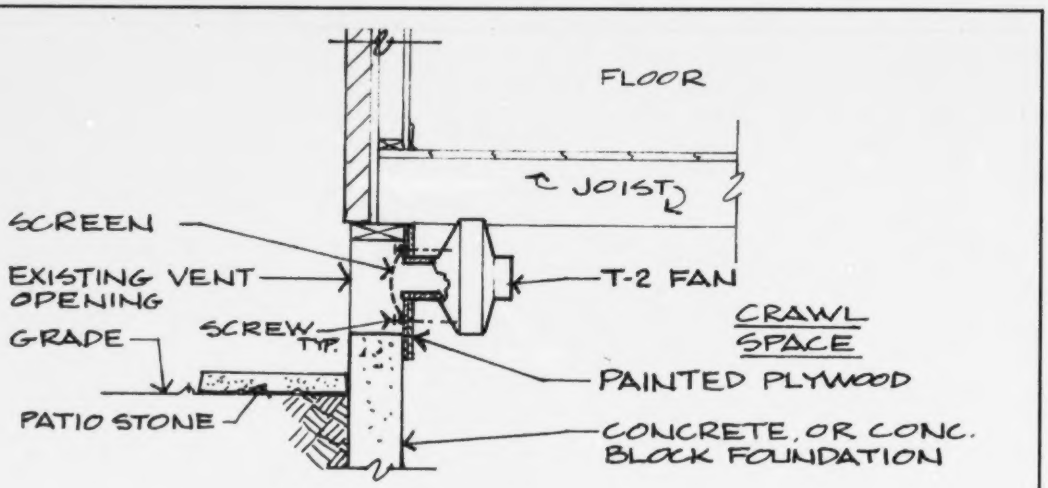
HOUSE NUMBER

33

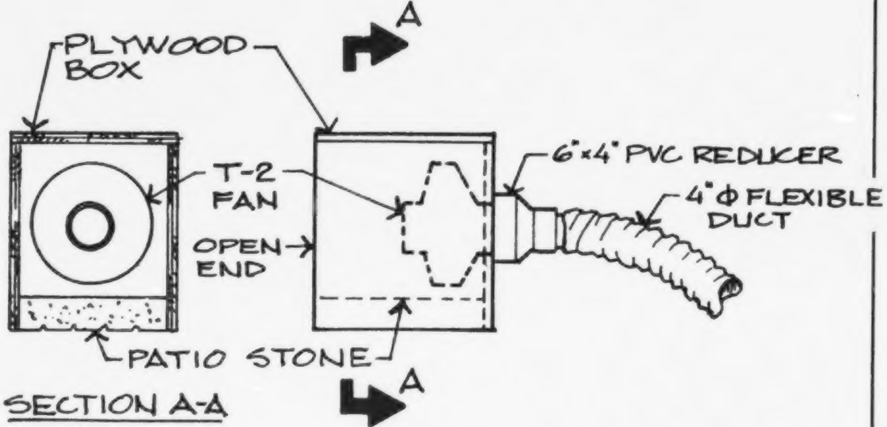


ACRES
Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
CRAWL SPACE	Date: MAY 1988	33
Mitigation system: CRAWL SPACE VENTILATION	PHASE: TEST AND FINAL	



FINAL SYSTEM
N.T.S.



TEST SYSTEM
N.T.S.

ACRES Acres International Corporation	LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
	SECTIONS/DETAILS	Date: MAY 1988	33
	Mitigation system: CRAWL SPACE VENTILATION	PHASE: TEST AND FINAL	

HOUSE 43

1 GENERAL DESCRIPTION

This large (180 m^2) single-story basement house with an attached garage was built in the early 1960's in a suburban subdivision in the south of Kettering. The basement foundation wall is of poured concrete. The exterior walls are of brick. Most of the basement is finished with paneling, floor tile and carpet, and contains a recreation room, study, sewing room, and washroom. The concrete floor is bare in the laundry room, a work shop, and in a storage room, all located along the front side of the basement. Heating is by an upflow forced air gas furnace with air conditioning located in the laundry room with the heat distribution ducts running the length of the house boxed into the recreation room ceiling. The water softener and the air conditioning condensate discharge to a small floor drain by the front wall of the laundry room. The grille over this floor drain was recessed down below the bottom of the slab; two interior drain tiles discharged into the drain above the grille, below the slab.

2 INVESTIGATION

In January 1988, a short-term continuous radon-monitor survey was conducted as part of the pre-selection process found that concentrations in the basement ranged from 11 to 25 pCi/L, averaging 16.5 pCi/L over 45 hours. Sub-slab communication tests were conducted during an EPA pre-selection visit. A 30-mm hole was drilled through the slab in the center of the laundry room and two 12-mm holes were drilled at distances of 30 cm (hole 1) and approximately 11 m (hole 2). Grab sampling showed that while the basement air had a radon concentration of 22 pCi/L, undisturbed samples from hole 1, hole 2 and the weeping tile contained 1400, 1100 and 580 pCi/L respectively. Suction of 270 Pa at the large hole produced exhaust radon concentration of 530 pCi/L and suctions of 32 and 10 Pa at holes 1 and 2. The near/far pressure ratio of 3:1 indicated very good sub-slab communication. With no suction being applied by the vacuum cleaner, the natural pressure differential across the slab was measured as 2 Pa (the sub-slab at a higher pressure than the house).

3 MITIGATION

As a result of the good results from the sub-slab communication test, the mitigation system chosen for demonstration was sub-slab exhaust with only one exhaust point. The installation was planned in two stages; a temporary system to check the effectiveness of the system, followed by a permanent installation.

In mid-March 1988, a temporary sub-slab ventilation system was installed. A 4-inch diameter hole was cored through the basement slab in the laundry room, adjacent to the bathroom wall; a 4-inch PVC pipe riser was inserted into the 20 cm of gravel beneath the slab. No hole was excavated under the slab where the pipe was placed, except to remove the gravel immediately under the slab hole. The piping was then run to an in-line T-2 centrifugal fan mounted outside a plywood insert in the laundry room window. To prevent house air from entering the sub-slab space through the floor drain opening, the floor drain was closed using a "Dranger" (a commercial retrofit trap designed for this purpose), which was foamed into place.

Before the sub-slab suction fan was turned on, radon levels in the basement ranged from 7 to 18 pCi/L, averaging 12.7 pCi/L over 65 hours. With the fan operating at maximum suction radon concentrations ranged from 0 to 3 pCi/L, averaging 0.5 pCi/L over 72 hours (Figure 43-3 plus the post-mitigation portion of Figure 43-2). The fan exhausted 13 L/s of 100-pCi/L air at a suction of 290 Pa in the fan riser. This gave a suction of 2 Pa at hole 2.

Since these radon concentrations were remarkably low, the fan suction was reduced to approximately half, to between 135 and 145 Pa at the riser, which provided a flow rate of 10 L/s. The suction at hole 2 remained at about 2 Pa. Radon concentrations in the basement ranged from 0 to 2 pCi/L, averaging 0.7 pCi/L over 65 hours (Figure 43-4).

With radon levels controlled by sub-slab suction, a test was made of the effectiveness of sub-slab pressurization. When the fan was reversed it provided an inflow of fresh air to the sub-slab space at 10 L/s under a pressure of 160 Pa. This led to basement levels of 3 to 10 pCi/L and an average of 5.3 pCi/L over 93 hours. Sub-slab pressurization lowered radon levels but was not as effective as sub-slab suction.

4 FINAL INSTALLATION

During the first week of April 1988, the floor-drain seal and the temporary sub-slab ventilation system were replaced by permanent systems. A 1.5" diameter straight length of plumbing pipe was attached to a 4-to-1.5" adaptor; the 4" end of the adaptor was cemented into the 4" diameter floor drain opening in the slab. The length of plumbing reached past the two open weeping-tile connections, to below the level of the water in the water-trap below the slab. This effectively closing the connection between the house and the internal weeping-tile. A standard plastic floor-drain connector and grille was fitted into the top of the adaptor, giving the assembly the appearance of a standard floor drain.

The original sub-slab ventilation pipe opening in the basement floor was retained, but some gravel was removed from beneath the hole to reduce flow resistance. The pipe was routed across the laundry room ceiling and into the garage through a 10 cm hole drilled in the concrete basement wall. From there, the pipe rises vertically through the garage ceiling and into the attic where the in-line T-2 centrifugal fan is located. The fan is secured between two rubber couplings close to a hole cut in the roof. The fan exhausts through a black ABS 10 cm plastic pipe rising 40 cm above the roof. The fan speed controller was located in the attic beside the entrance hatch.

The fan speed was set to give a suction of 200 Pa and a flow rate of 31 L/s, and radon concentrations in the basement ranged from 0 to 1 pCi/L, and averaged 0.4 pCi/L over 70 hours.

During the summer, the owner reported that the fan had stopped operating. This was a summer of record temperatures, and temperatures in the attic were as high as 50°C, which was probably too high for the solid-state fan-speed controller to tolerate. The fan was wired directly to the main supply. and ran correctly, so it had not been affected by the heat.

5 OTHER MEASUREMENTS

The 1987 charcoal canister test gave a radon value of 22.8 pCi/L in the basement. A later canister test, in December 1987, indicated an upstairs value of 8.5 pCi/L in the living room. A short-term radon-monitor survey in January 1988 found concentrations in the basement ranged from 11 to 25 pCi/L, averaging 16.5 pCi/L.

Pre-mitigation alpha-track measurements over the period December 1987 to February 1988 gave average radon concentrations of 6.3 pCi/L in the living area, and 8.0 and 11.3 pCi/L in two simultaneous measurements in the basement.

Post-mitigation alpha-track measurements over the period May to August 1988 gave an average radon concentrations of 1.1 pCi/L in the living area and 2.3 pCi/L in the basement.

The radiation field in the basement ranged from 5 to 6 μR/h over the entire floor slab. The field over the site outside the house ranged from 7 to 9 μR/h, averaging 8 μR/h.

MEASUREMENTS SUMMARY FOR HOUSE 43

PYLON AB-5 HOURLY MONITORING

MITIGATION SYSTEM	TEST DATE	TEST STATUS	RADON (pCi/L) RANGE	RADON (pCi/L) MEAN	DURATION	FIG.
pre-selection	01/88		11-25	16.5	45 hrs	43-1
sub-slab suction	03/88	fan off	7-18	12.7	65 hrs	43-2
		DPmax	1- 3	2.0	6 hrs	43-2
	03/88	DPmax	0- 1	0.4	66 hrs	43-3
		0.5DPmax	0- 2	0.7	65 hrs	43-4
sub-slab pressured	03/88	0.5DPmax	3-10	5.3	93 hrs	43-5
sub-slab suction (permanent)	04/88	DPmax	0- 1	0.4	70 hrs	43-6

Average pre-mitigation Pylon results in basement (presented in Tables IV, V and 3):

Weighted average of Figure 43-1 and pre-mitigation (fan-off) portion of Figure 43-2 (110 hours total) = 14.3 pCi/L.

Average post-mitigation Pylon results (sub-slab suction with fan at 0.5 DPmax, presented in Tables IV and V):

Weighted average of Figures 43-4 and 43-6 (135 hours total) = 0.5 pCi/L.

SYSTEMS MEASUREMENTS

PHASE	MITIGATION SYSTEM	TEST DATE	MEASUREMENTS			COMMENT
			SUCTION (Pa)	FLOW (L/s)	RADON (pCi/L)	
I	pre-selection	01/88			22	basement air
					1400	hole 1
					1100	hole 2
					580	weeping tile
			270		530	suction at slab
			32			at hole 1
			10			at hole 2
			-2*			at slab; natural
I	sub-slab suction	03/88	270-290	13	100	at riser; DPmax
			6			at hole 2
			135-145	10		at riser; 0.5DPmax
			2			at hole 2
I	sub-slab pressured	03/88	-160*	10		at riser; 0.5DPmax
I	sub-slab suction (permanent)	04/88	200	31		at riser; DPmax

* "Negative suction" denotes pressurization relative to house.

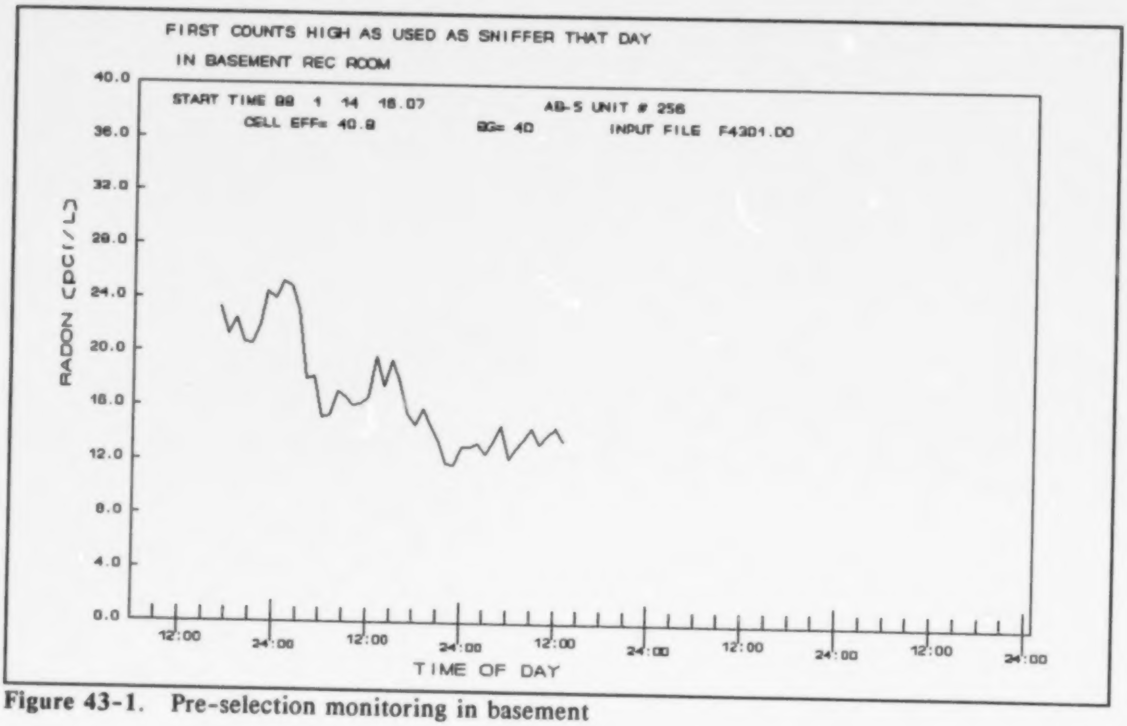


Figure 43-1. Pre-selection monitoring in basement

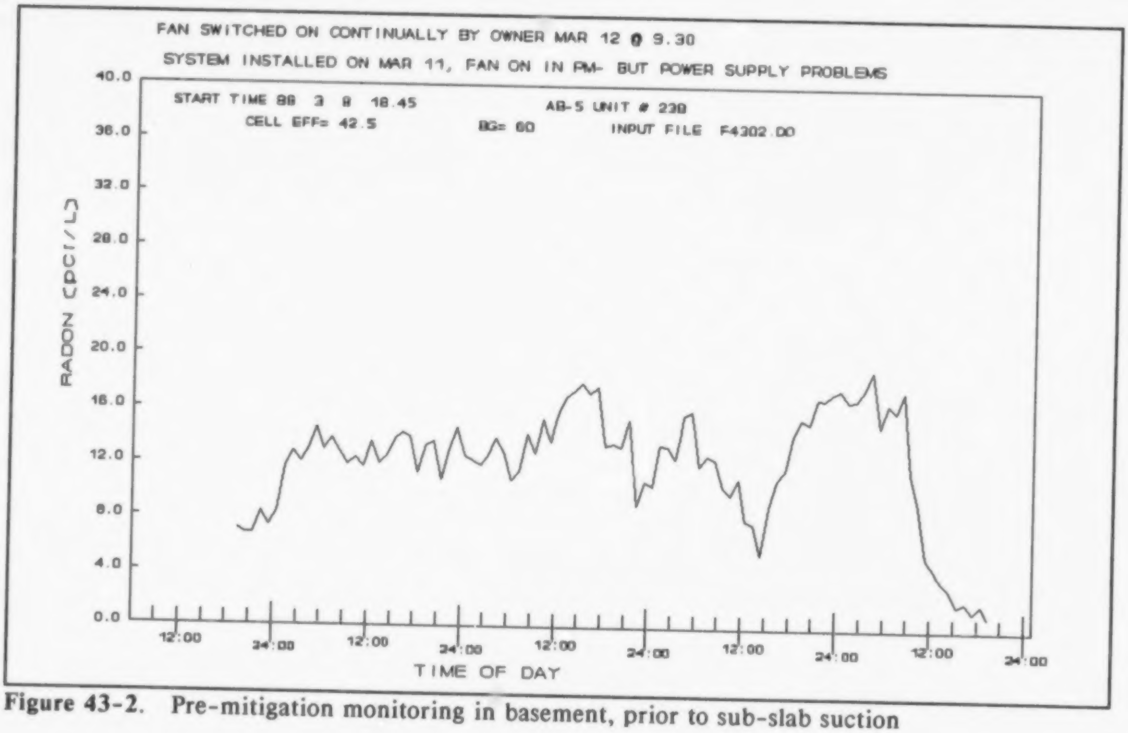


Figure 43-2. Pre-mitigation monitoring in basement, prior to sub-slab suction

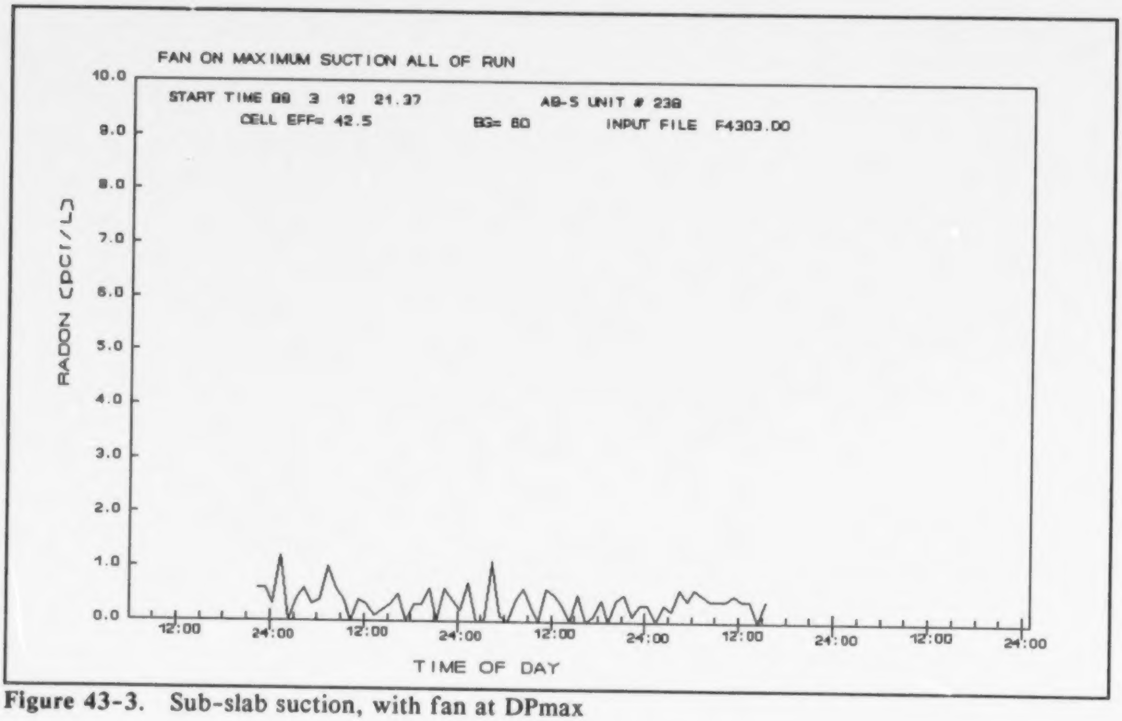


Figure 43-3. Sub-slab suction, with fan at DPmax

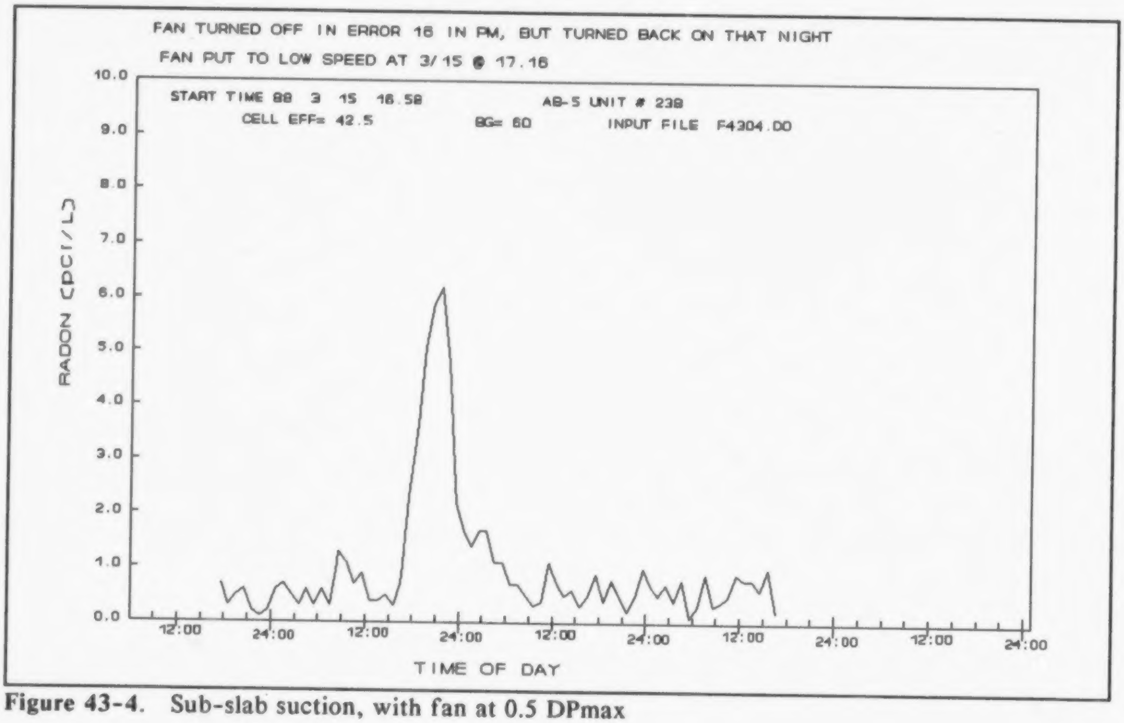


Figure 43-4. Sub-slab suction, with fan at 0.5 DPmax

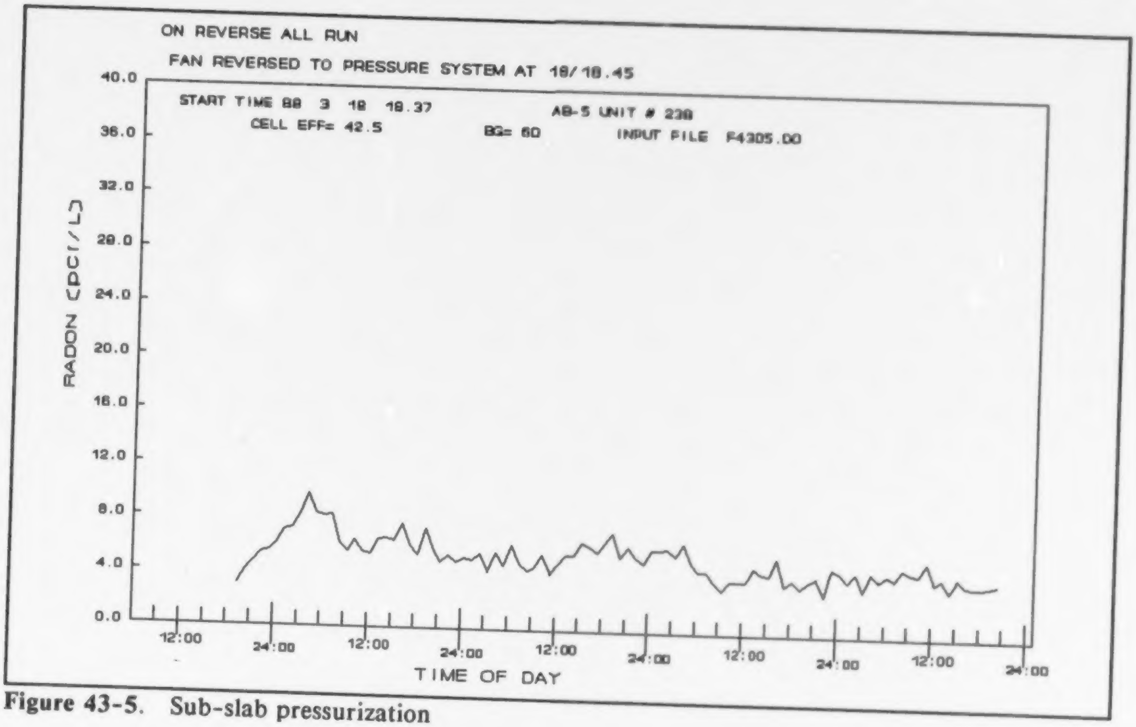


Figure 43-5. Sub-slab pressurization

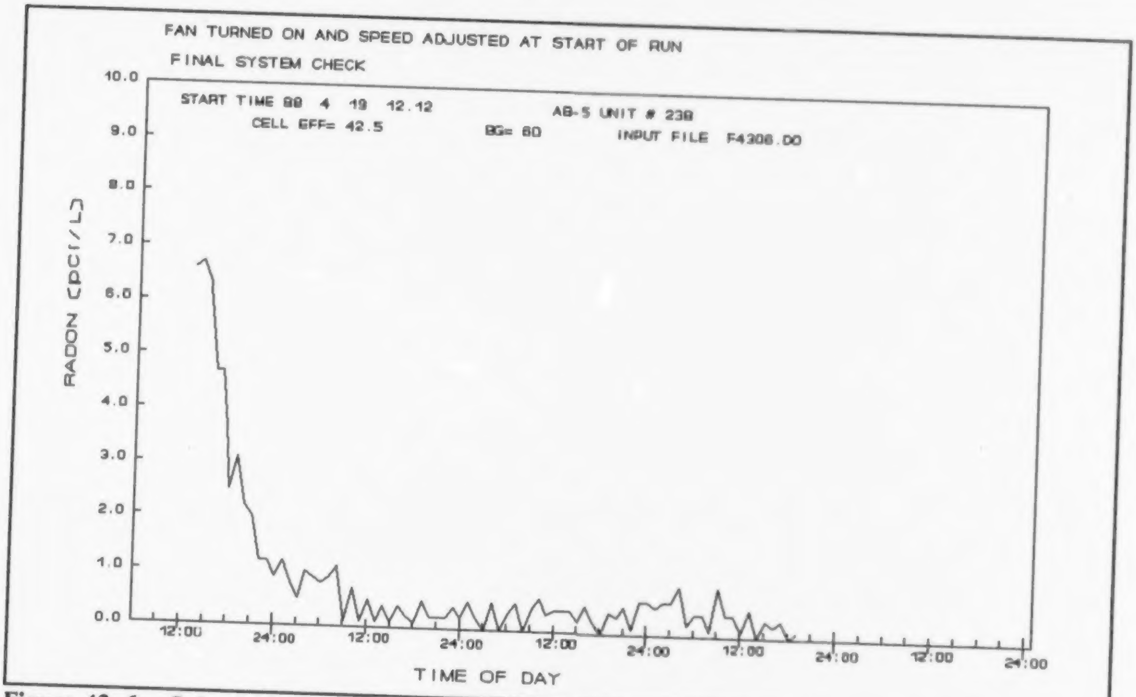
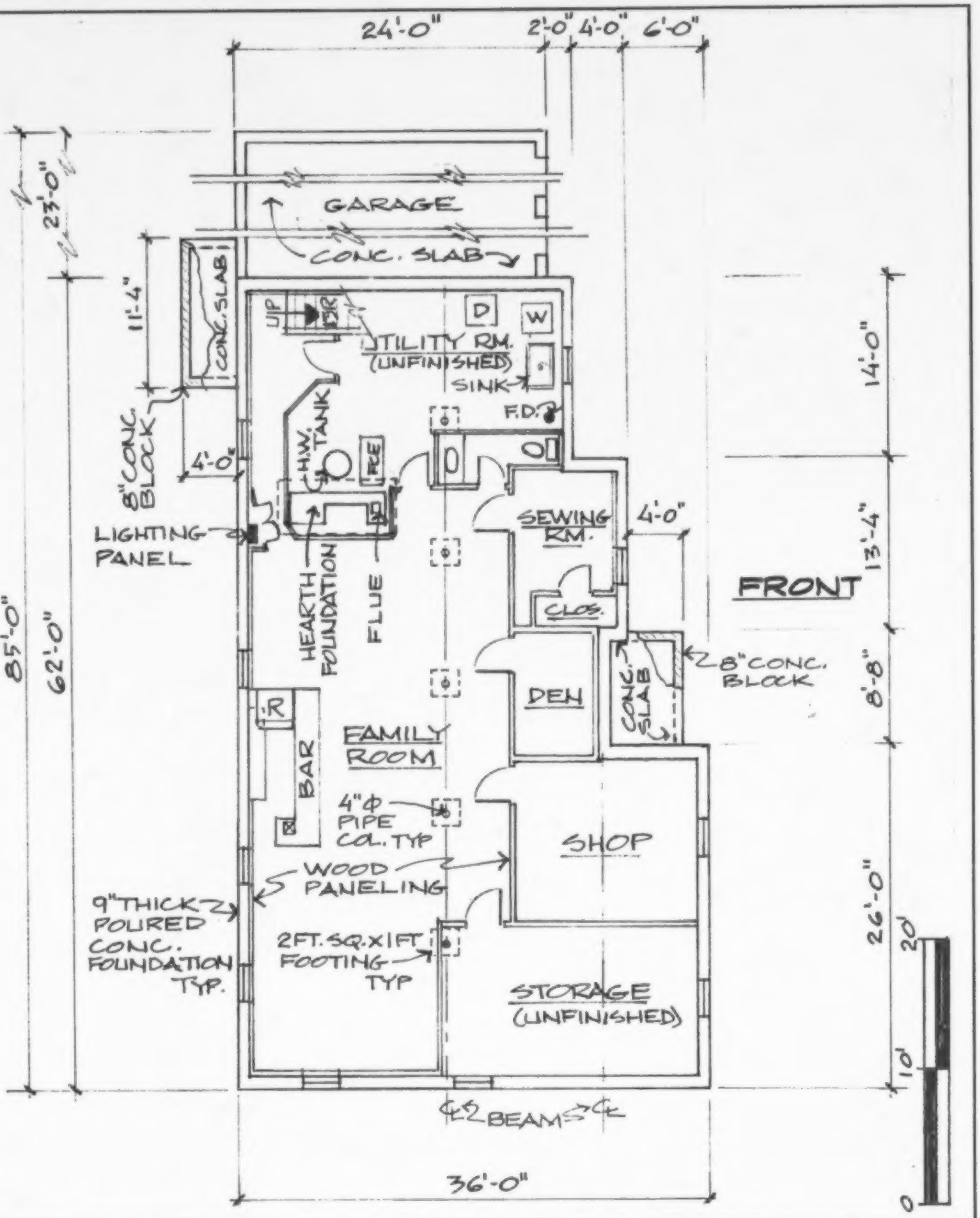


Figure 43-6. Sub-slab suction (permanent installation)



ACRES
Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON

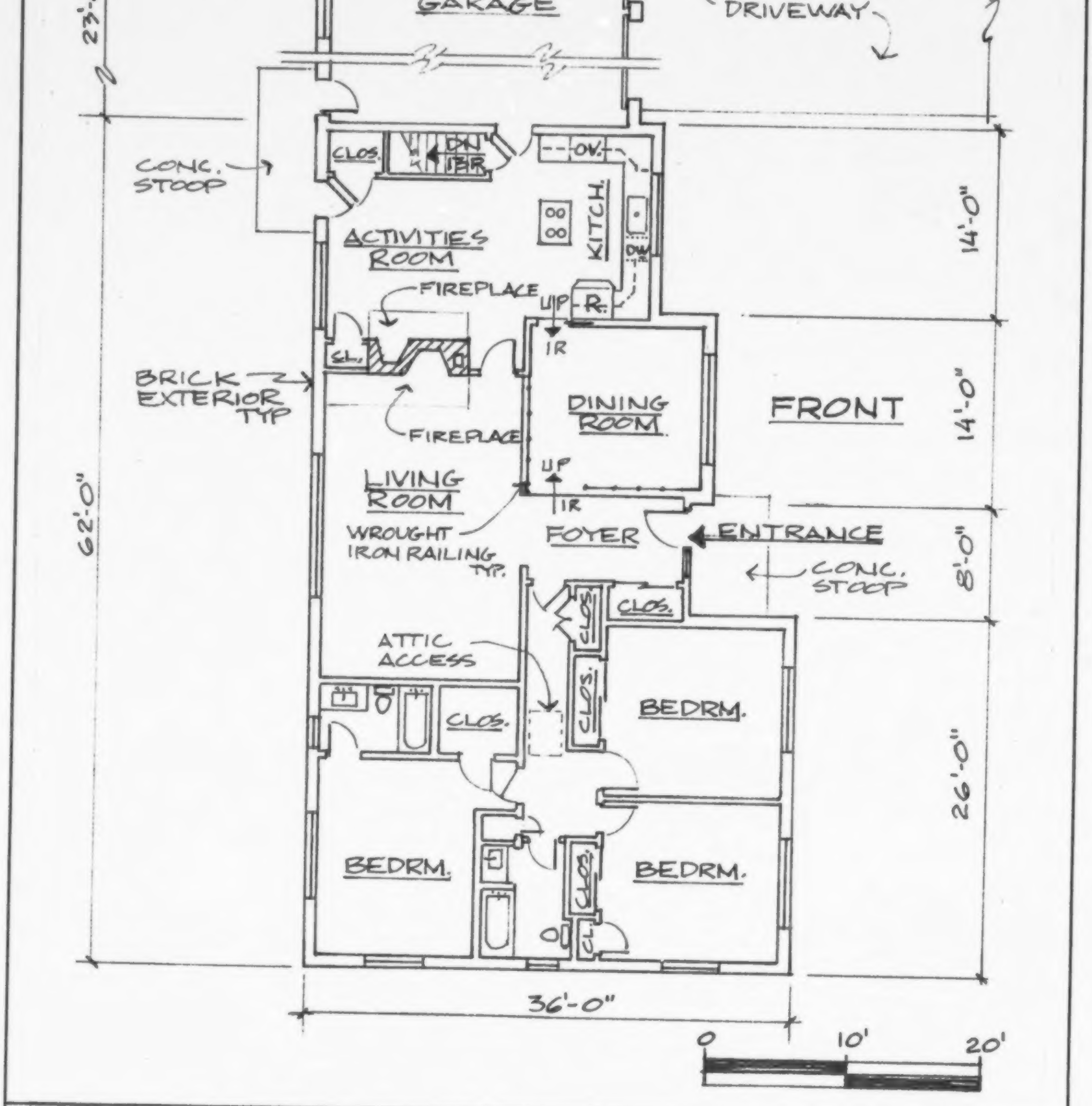
BASEMENT/FOUNDATION PLAN

House Group: FULL BASEMENT

HOUSE NUMBER 43

Date: 2/24/88

PHASE:



ACRES
Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON

GRADE LEVEL PLAN

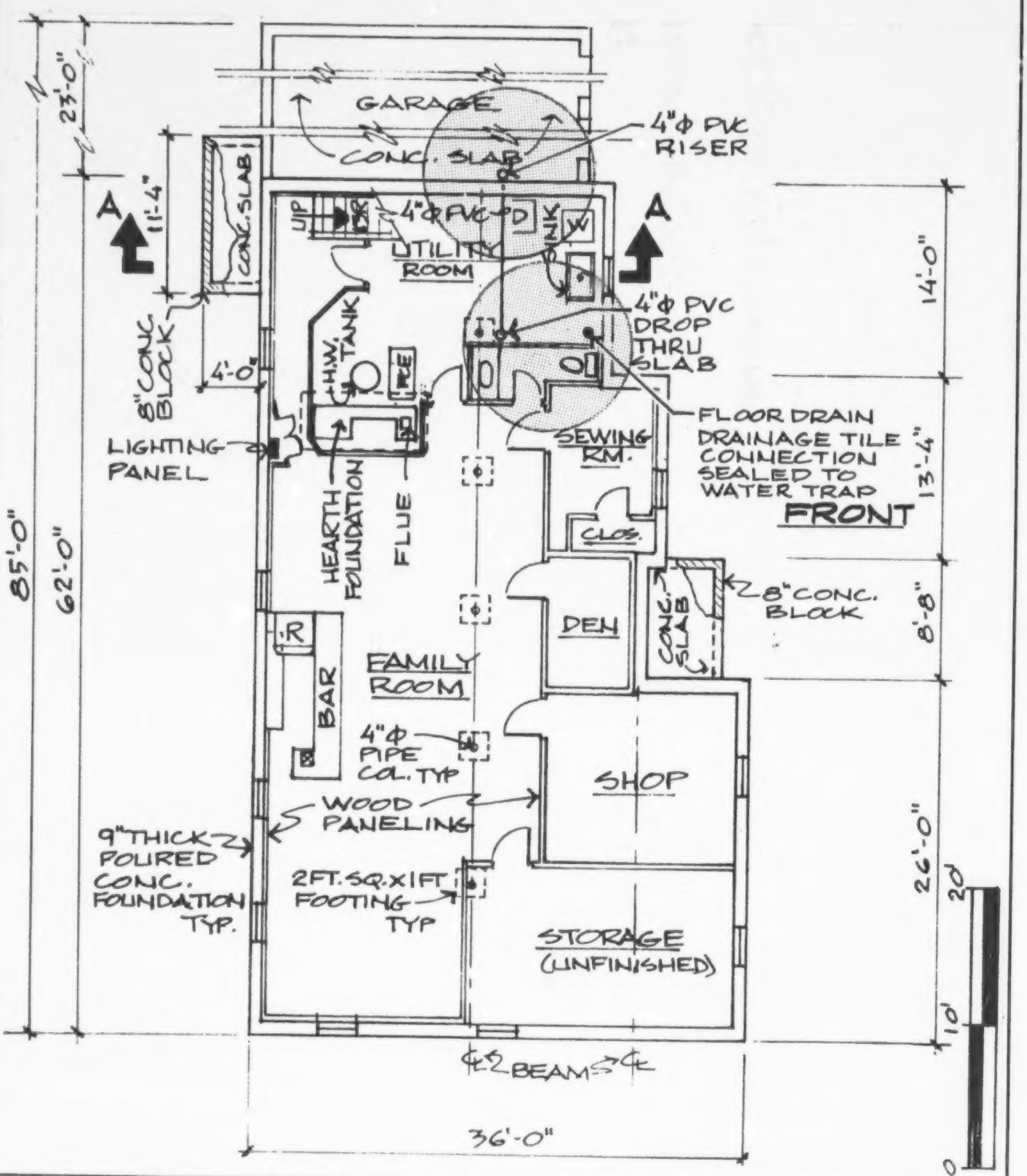
Date: 2/24/88

House Group: **FULL BASEMENT**

PHASE:

HOUSE NUMBER

43



ACRES
Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON

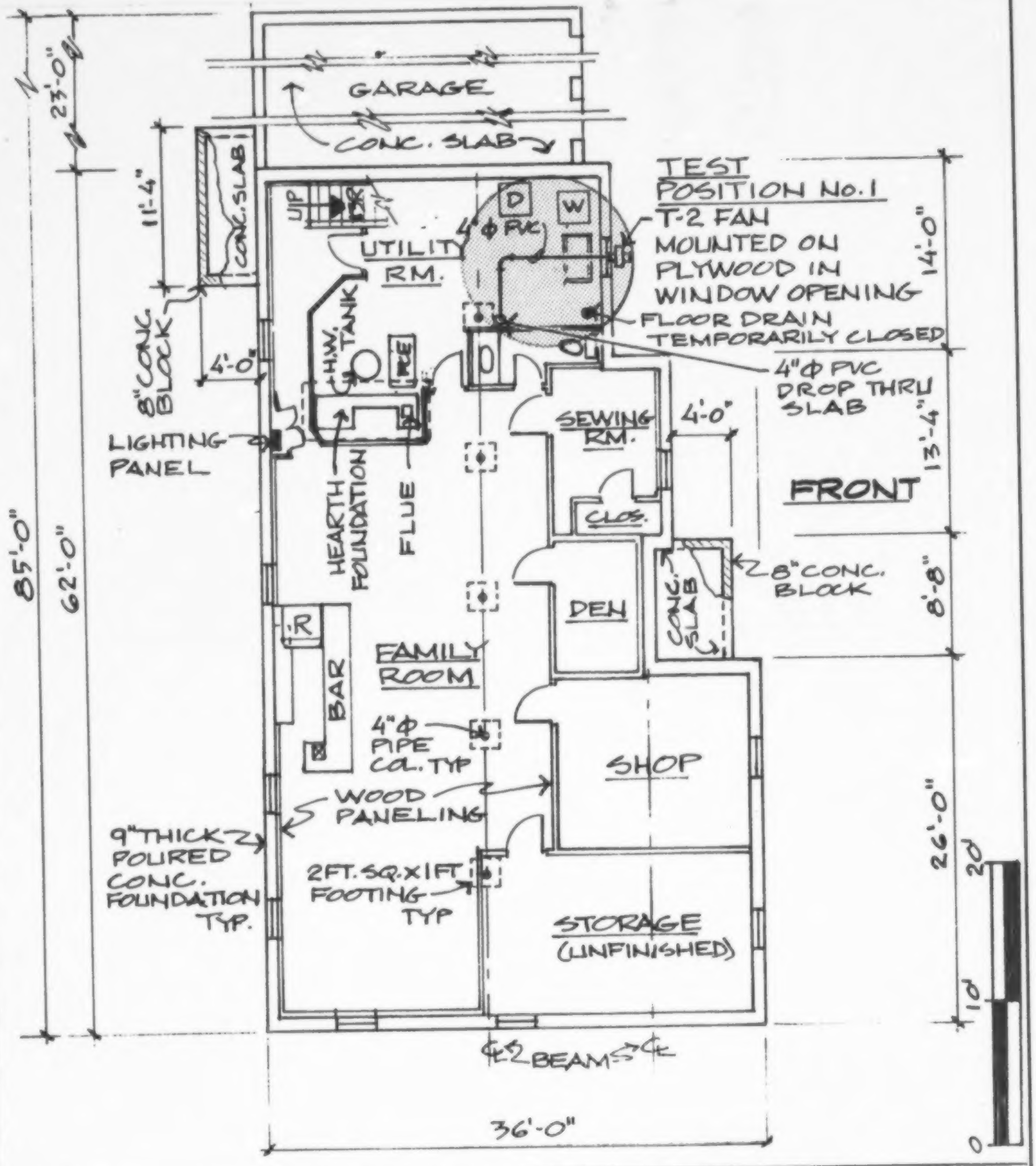
HOUSE NUMBER 43

BASEMENT/FOUNDATION PLAN

Date: MAY 1988

Mitigation system: SUB-SLAB SUCTION

PHASE: FINAL



ACRES
Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON

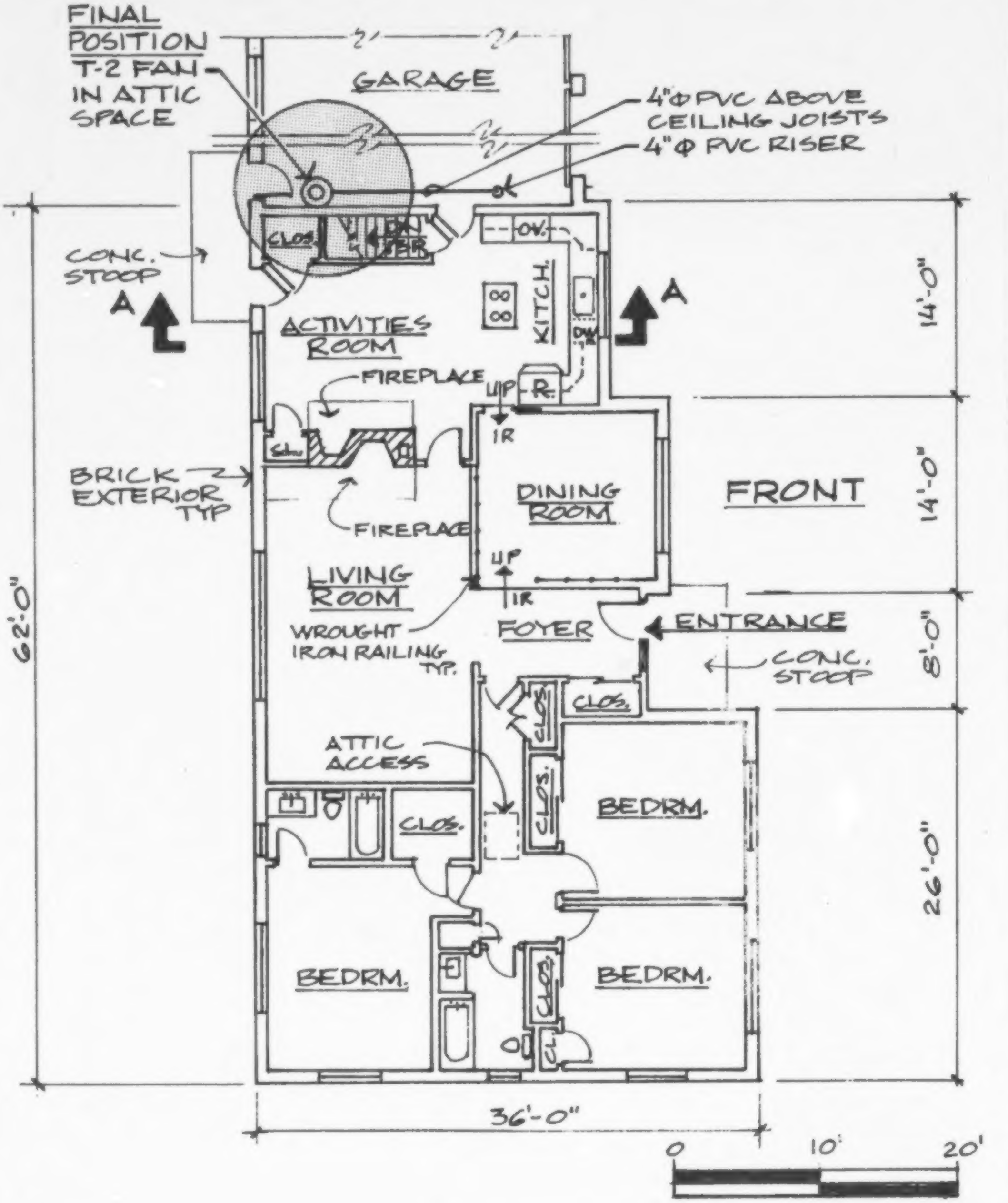
BASEMENT/FOUNDATION PLAN

Mitigation system: SUB-SLAB SUCTION

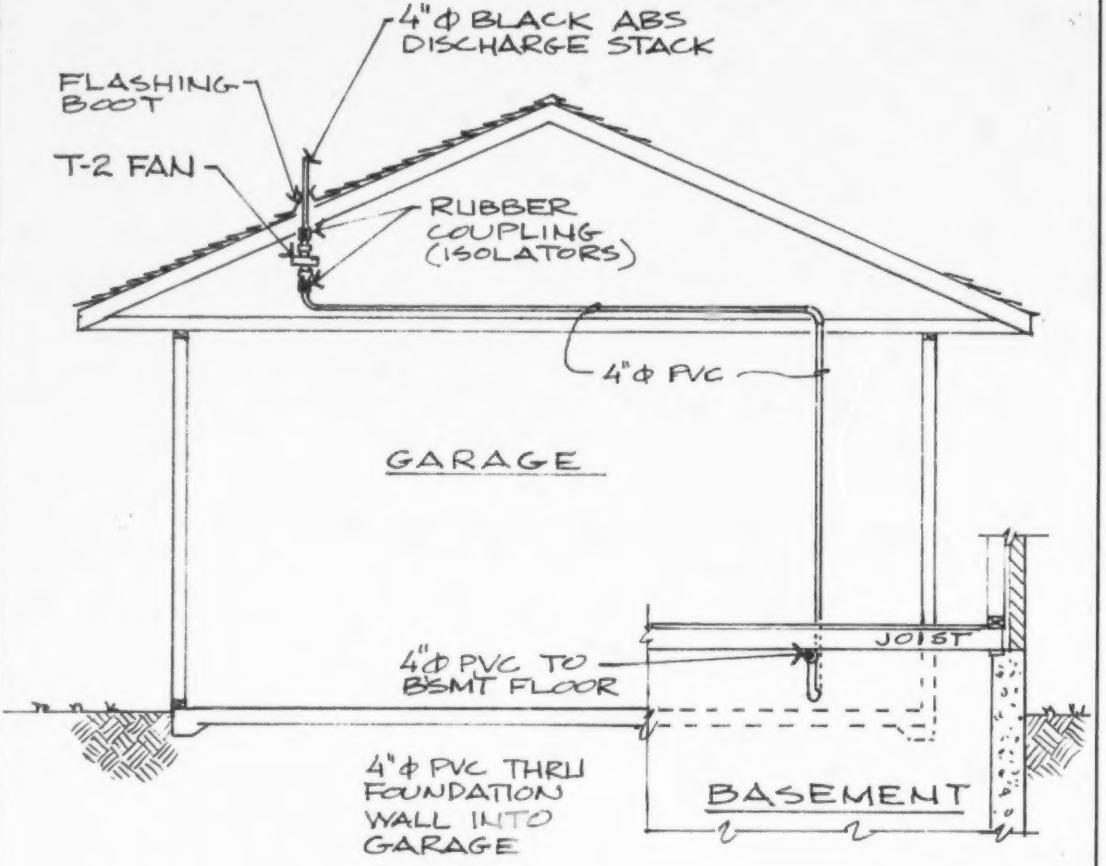
Date: MAY 1988

PHASE: TEST

HOUSE NUMBER 43



ACRES Acres International Corporation	LOW COST REDUCTION OF INDOOR RADON	HOUSE NUMBER
	GRADE LEVEL PLAN	Date: MAY 1988
	Mitigation system: SUB-SLAB SUCTION	PHASE: FINAL
		43


4"Φ BLACK ABS DISCHARGE STACK
FLASHING BOOT
T-2 FAN
RUBBER COUPLING (ISOLATORS)
4"Φ PVC
GARAGE
JOIST
4"Φ PVC TO B'SMT FLOOR
4"Φ PVC THRU FOUNDATION WALL INTO GARAGE
BASEMENT

SECTION A-A
N.T.S.

ACRES Acres International Corporation	LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
	SECTIONS/DETAILS	Date: MAY 1988	43
	Mitigation system: SUB-SLAB SUCTION	PHASE: FINAL	

HOUSE 45

1 GENERAL DESCRIPTION

This small (90 m^2) single-story basement house with an attached garage was built in the late 1950's in a suburban subdivision just to the east of Kettering. The exterior walls are of brick, the basement walls are of poured concrete. Most of the basement is finished with panelled walls, a plaster ceiling and tiled floor. Minor floor-cracking, and an open (1 mm) wall/floor joint are visible in the unfinished area. Heating is by an upflow forced-air gas furnace with air conditioning centrally located in the basement with metal heat distribution ducts running along the ceiling for the length of the house. This is supplemented by stand-alone unvented kerosene heaters upstairs and in the basement.

The floor drain is trapped, but there is a weeping tile entry into the floor drain above the water level in the trap. The condensate from the air conditioner discharges to the floor drain.

2 INVESTIGATION

In January 1988, a short-term radon-monitor survey conducted as part of the pre-selection process found concentrations in the basement ranged from 10 to 29 pCi/L, averaging 19.8 pCi/L over 22 hours. Sub-slab communication tests were conducted during an EPA pre-selection visit. Grab sampling showed that while the basement air contained a radon concentration of 28 pCi/L, undisturbed samples at the floor drain and at hole 2, a 12-mm hole drilled through the slab at a distance of 5 m from the drain, contained 920 and 1300 pCi/L. When 490 Pa of suction were applied to the floor drain, in which the weeping tile entered above the water trap, a suction of 20 Pa was produced at hole 2, indicating that there was communication from the drain to the sub-slab space.

3 MITIGATION

As a result of the good results from the sub-slab communication test, the mitigation system chosen for demonstration was sub-slab exhaust. The installation was planned in two stages; a temporary system to check the effectiveness of the system, followed by a permanent installation.

A temporary single-point sub-slab suction system was installed at the beginning of March 1988. A 4-inch diameter hole was cored in the slab close to the house centerline in the middle of the unfinished area. A run of 4-inch PVC pipe was fashioned to circumvent existing furnace ducts connecting to a Kanalflakt T-2 in-line centrifugal fan mounted outside a plywood window insert; a fan-speed controller was attached. A temporary seal was created at the floor drain by inserting a straight length of 1.5" plastic plumbing pipe vertically down to below the water surface in the trap, and filling the annular gap between the 1.5" plumbing pipe and the 4" drain opening through the slab with expanding urethane foam. This effectively closed the weeping tile connection, and prevented air from being drawn into the sub-slab space from the house.

With the system fan turned off, radon monitoring was conducted both before and after the drain was sealed. Previous to closure, levels ranged from 7 to 30 pCi/L, averaging 20.9 pCi/L over 27 hours, whereas, after closure levels ranged from 10 to 15 pCi/L, averaging 11.6 pCi/L over 15 hours. Thus some improvement was achieved by sealing the floor drain, but this was not the complete answer.

When the system fan was turned on at maximum setting the suction was 250 Pa, at a flow rate of 18 L/s and exhaust radon concentrations of approximately 250 pCi/L. Basement radon concentrations fell quickly to range from 1 to 4 pCi/L, and averaged 2.2 pCi/L over 90 hours (Figure 45-3).

The fan speed was reduced to give a flow of 16 L/s at 250 Pa. At this setting, radon concentrations in the basement ranged from 0 to 4 pCi/L and averaged 2.0 pCi/L over 76 hours (DPlow portion of Figure 45-4).

The fan was then adjusted to approximately half maximum suction, or 140 Pa at the riser providing a flow rate of 11 L/s. Sub-slab suction was still very effective at that much lower setting. Radon concentrations ranged from 1 to 3 pCi/L, averaging 1.5 pCi/L over 120 hours (Figure 45-5 and 0.5 DPmax portion of Figure 45-4).

4 FINAL INSTALLATION

At the end of March 1988, the mitigation system was made permanent. The temporary floor drain closure was removed. A new closure assembly was installed, involving a 2-inch diameter pipe which went vertically down to below water level in the trap, and which on top connected to a 3-inch diameter segment; the 3" diameter segment was grouted into place in the opening through the slab which accommodated the floor drain. The ventilation system piping was routed to a new exit via a 4" hole cut in the rear concrete wall just above grade level. An outdoor riser was then led through the eaves to a Kanalflakt centrifugal ventilator fan on the roof. Electrical wiring was run from the fan, down through the pipe, to the electrical panel and speed controller in the basement.

The fan speed was set to give approximately 130 Pa (half the maximum suction), the radon concentration in the fan effluent was 250 pCi/L. Under these conditions, the basement radon concentrations ranged from 1 to 2 pCi/L, averaging 1.1 pCi/L over 69 hours.

5 OTHER MEASUREMENTS

The 1987 charcoal canister test gave a radon value of 117 pCi/L above the floor drain in the basement. An additional canister test in December 1987 found basement levels averaged 26 pCi/L. A short-term continuous radon-monitor survey in January 1988 found concentrations in the basement ranged from 10 to 29 pCi/L, averaging 19.8 pCi/L.

Pre-mitigation alpha-track measurements over the period December 1987 to February 1988 gave average radon concentrations of 8.5 pCi/L in the kitchen and 19.8 pCi/L in the basement.

Post-mitigation alpha-track measurements over the period May to August 1988 gave an average radon concentrations of 1.1 pCi/L in the living area, and 1.0 pCi/L in the basement.

The gamma radiation field in the house was about 5 μR/h, and the gamma field over the site on the site ranged from 6 to 8 μR/h, averaging 7 μR/h.

MEASUREMENTS SUMMARY FOR HOUSE 45

PYLON AB-5 HOURLY MONITORING

MITIGATION SYSTEM	TEST DATE	TEST STATUS	RADON (pCi/L) RANGE	RADON (pCi/L) MEAN	MONITOR DURATION	FIG.
pre-selection	01/88		10-29	19.8	22 hrs	45-1
floor-drain closed	03/88	before	7-30	20.9	27 hrs	45-2
		after	10-15	11.6	15 hrs	45-2
sub-slab suction (+ floor-drain sealed)	03/88	DPmax	1- 4	2.2	90 hrs	45-3
		DPlow	0- 4	2.0	76 hrs	45-4
		0.5DPmax	1- 3	1.7	22 hrs	45-4
		0.5DPmax	1- 3	1.5	98 hrs	45-5
sub-slab suction (permanent installation)	04/88	0.5DPmax	1- 2	1.1	69 hrs	45-6

Average pre-mitigation Pylon results (presented in Tables IV and 3):

> Weighted average of Figure 45-1 and before-closure portion of Figure 45-2 (49 hours total) = 20.5 pCi/L.

Average post-mitigation Pylon results (sub-slab suction with fan at 0.5 DPmax, presented in Table IV):

> Weighted average of Figures 45-4 (portion at 0.5 DPmax) and 45-5 (120 hours total) = 1.5 pCi/L.

SYSTEMS MEASUREMENTS

PHASE	MITIGATION SYSTEM	TEST DATE	MEASUREMENTS			COMMENT
			SUCTION (Pa)	FLOW (L/s)	RADON (pCi/L)	
1	pre-selection	01/88	490		920	suction applied to floor drain
			20		1300	at hole 2
					28	basement air
1	sub-slab suction (+ floor-drain sealed)	03/88	260	18	250	riser; DPmax
					2	basement air
			250	16		riser; DPlow
			140	11		riser; 0.5DPmax
1	sub-slab suction (permanent installation)	04/88	270-290	21		riser; DPmax
			125-135		250	riser; 0.5DPmax

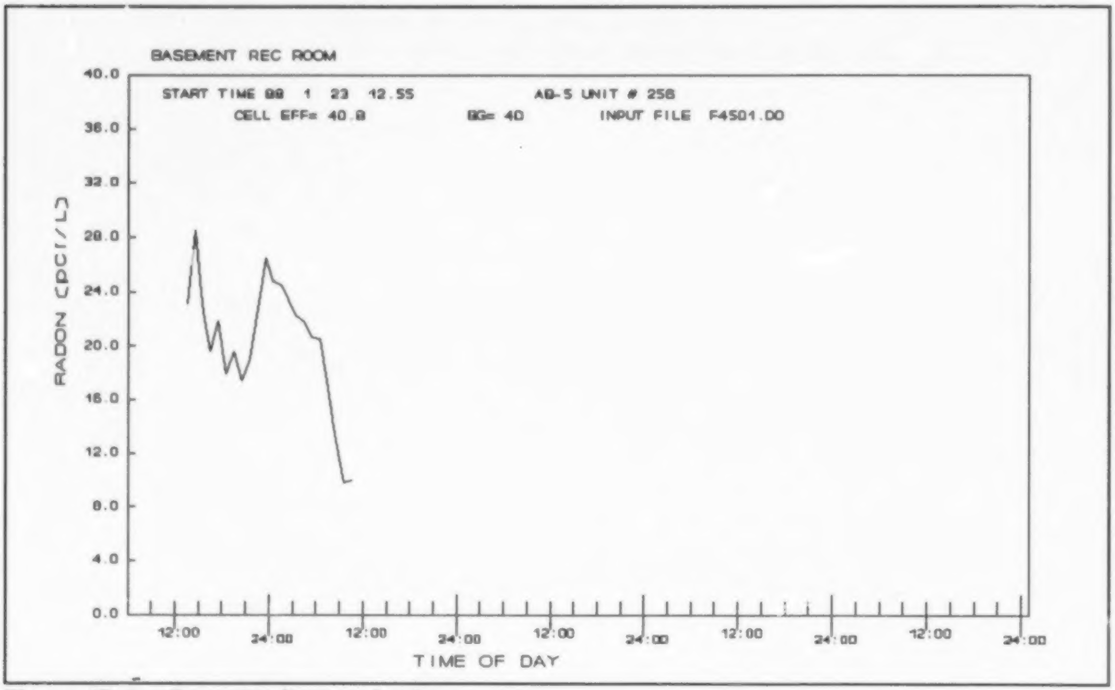


Figure 45-1. Pre-selection monitoring

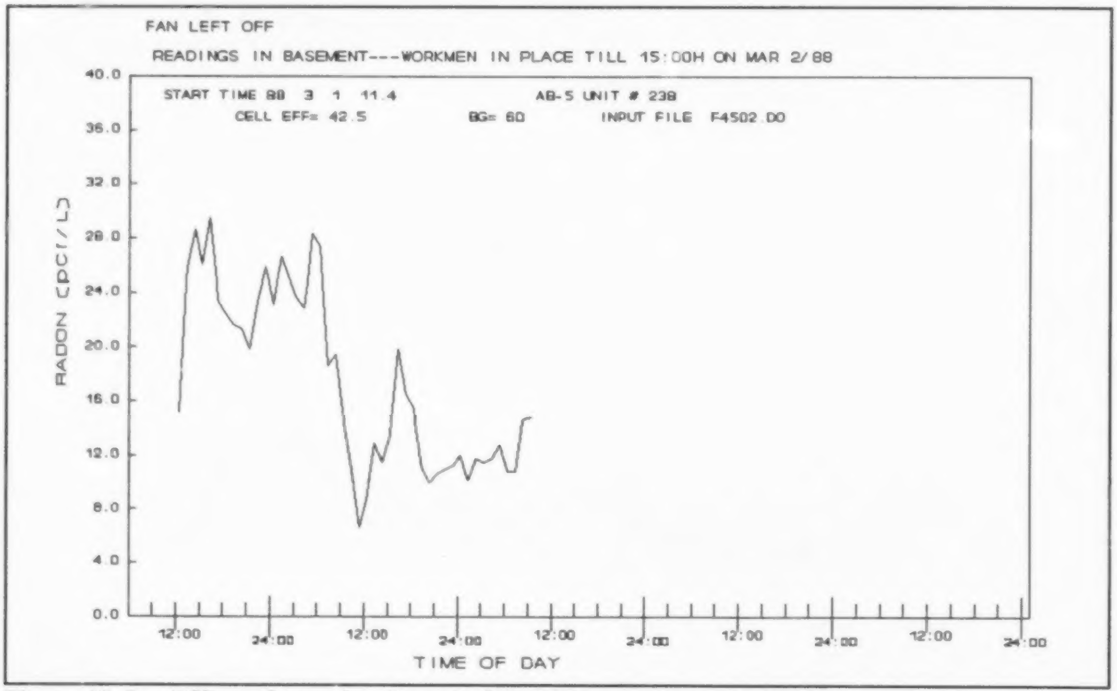


Figure 45-2. Effect of trapping floor drain which connects to drain tiles

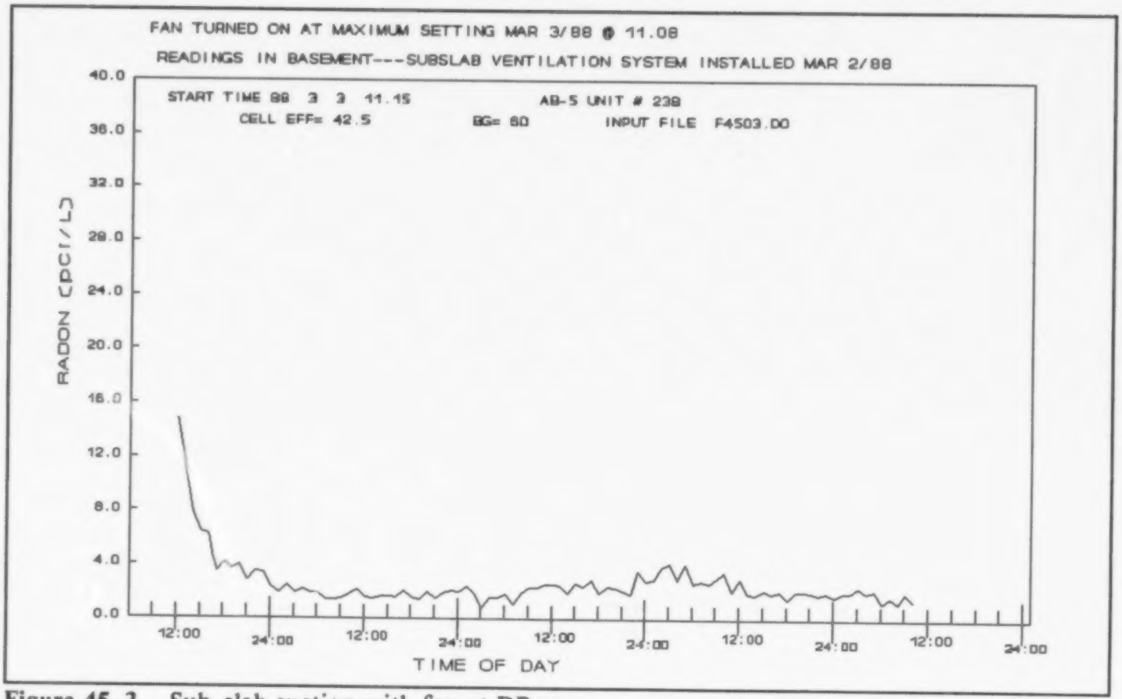


Figure 45-3. Sub-slab suction with fan at DPmax

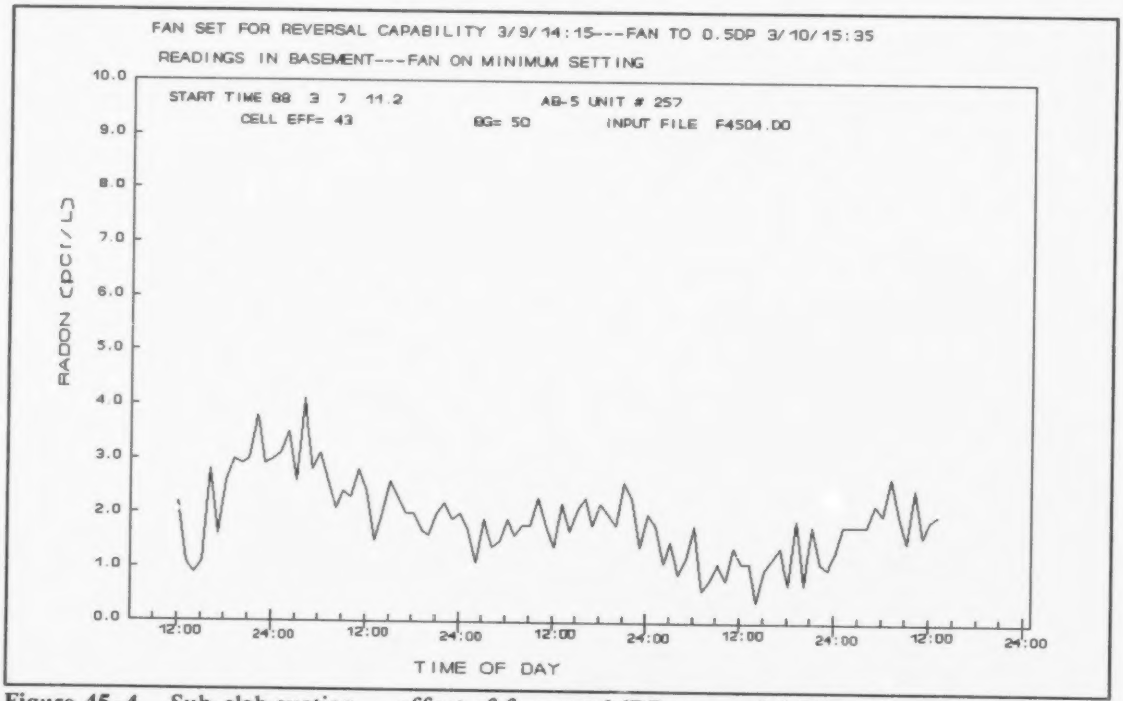


Figure 45-4. Sub-slab suction -- effect of fan speed (DPmax vs. 0.5 DPmax)

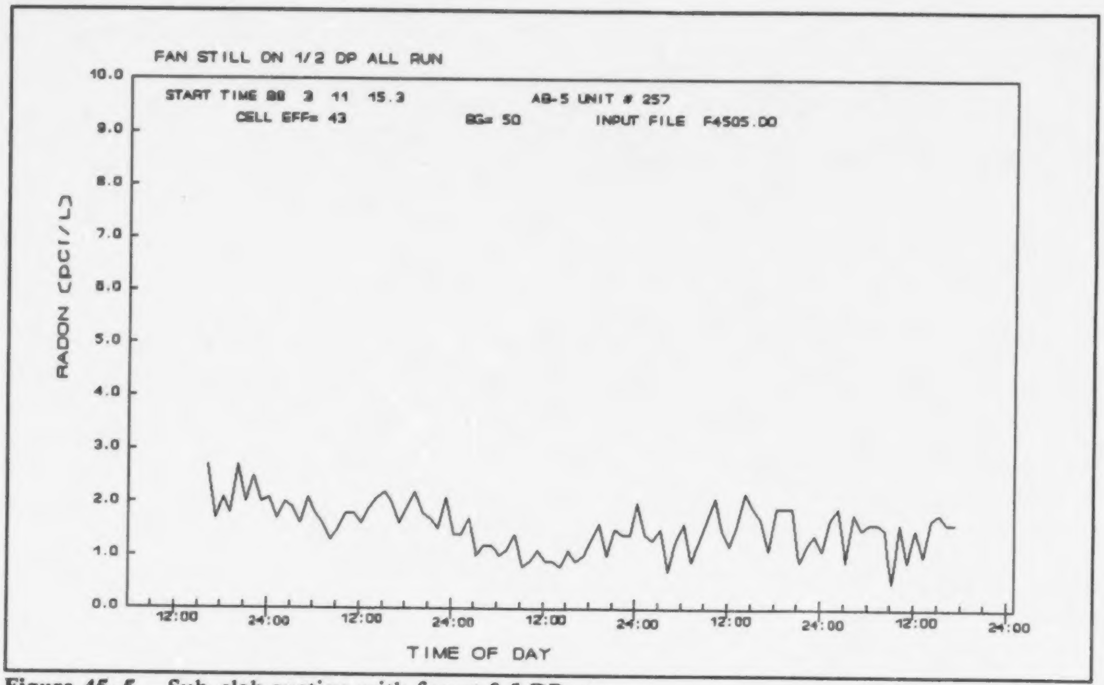


Figure 45-5. Sub-slab suction with fan at 0.5 DPmax

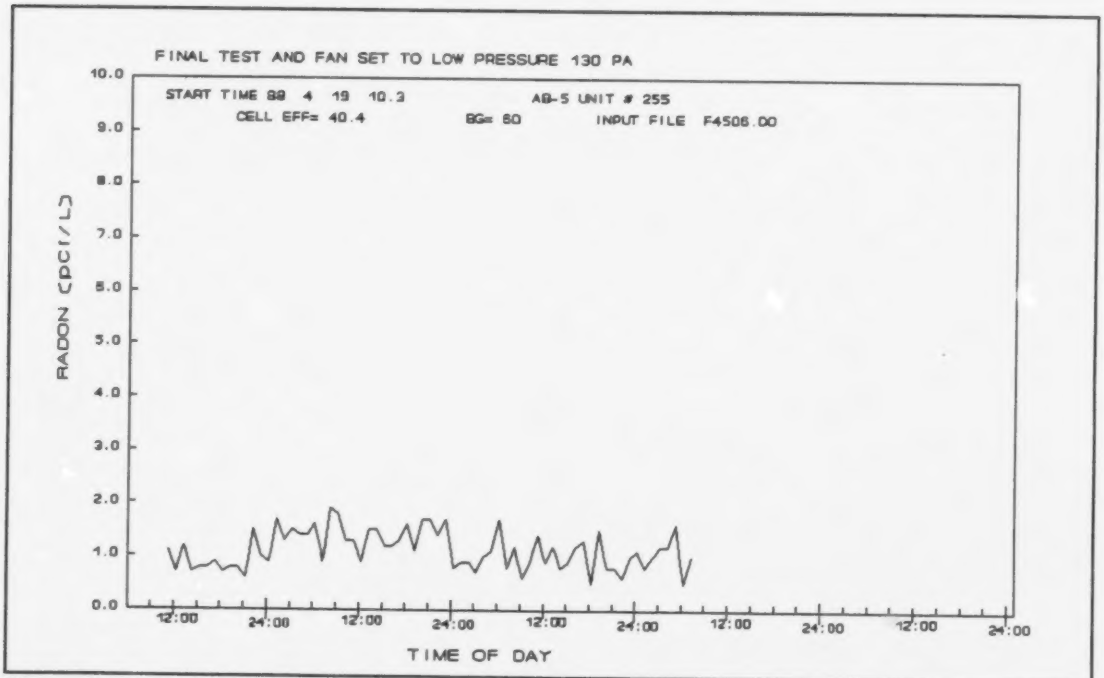
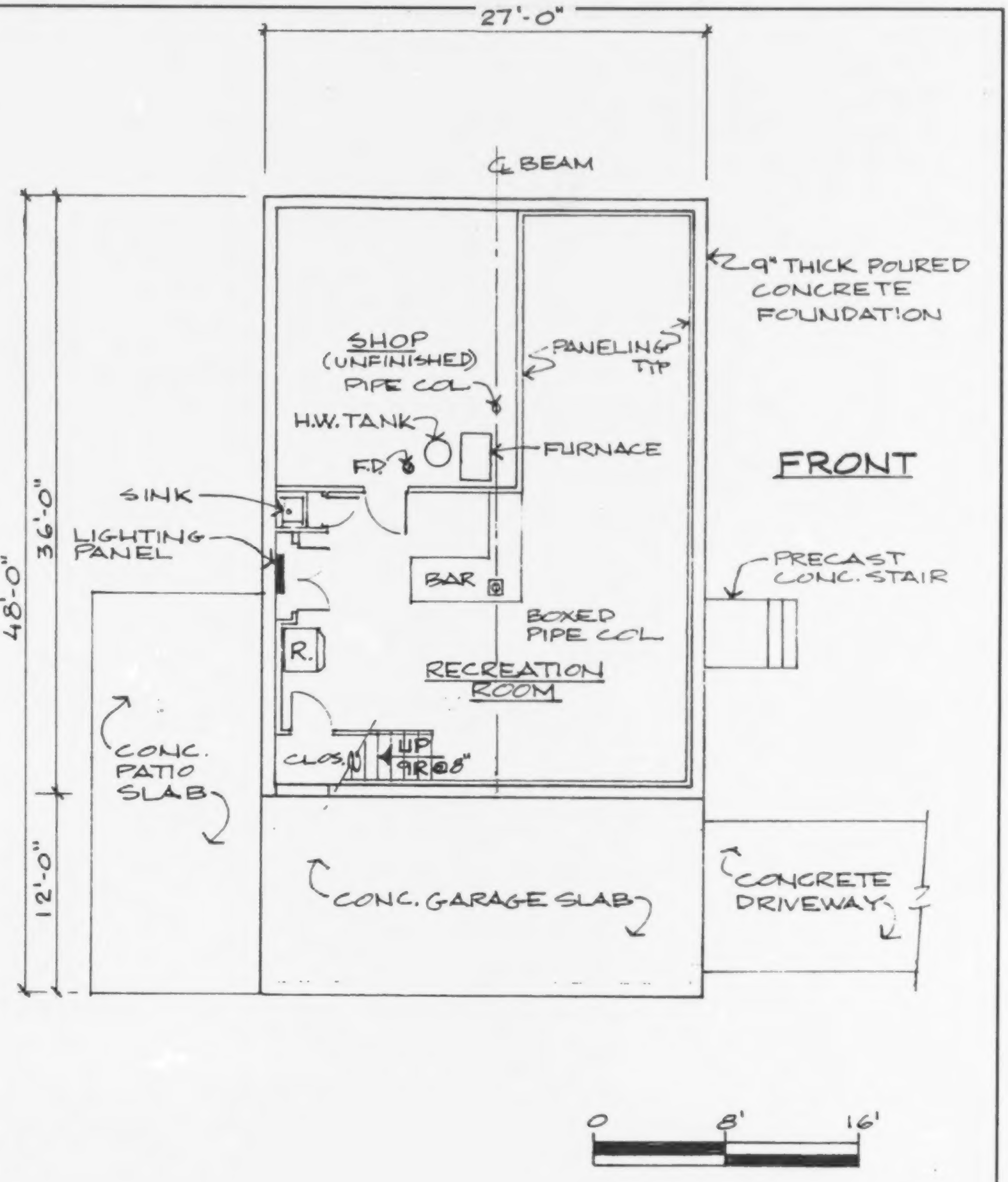


Figure 45-6. Sub-slab suction (permanent installation)



ACRES

LOW COST REDUCTION OF INDOOR RADON

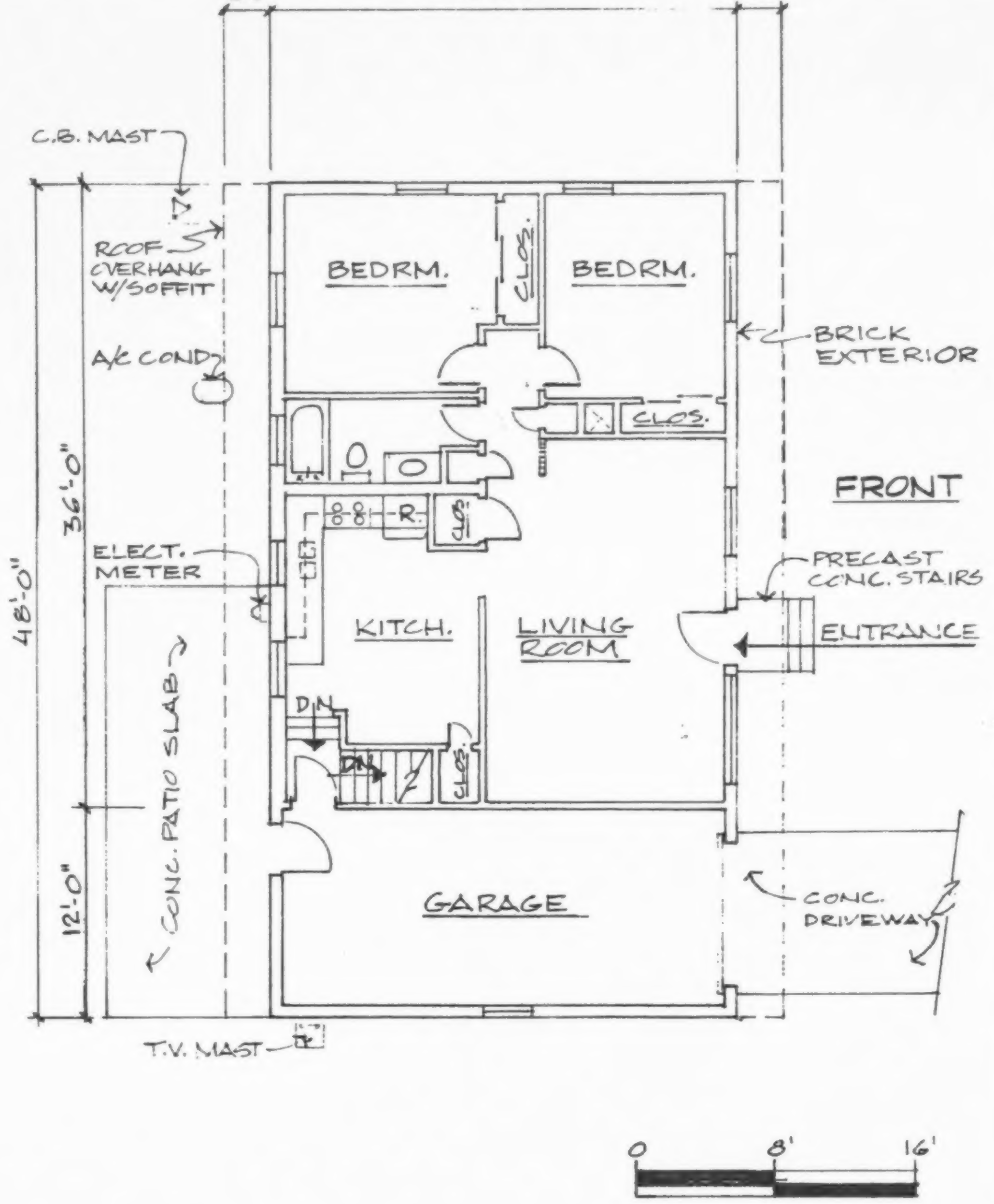
HOUSE NUMBER 45

BASEMENT/FOUNDATION PLAN

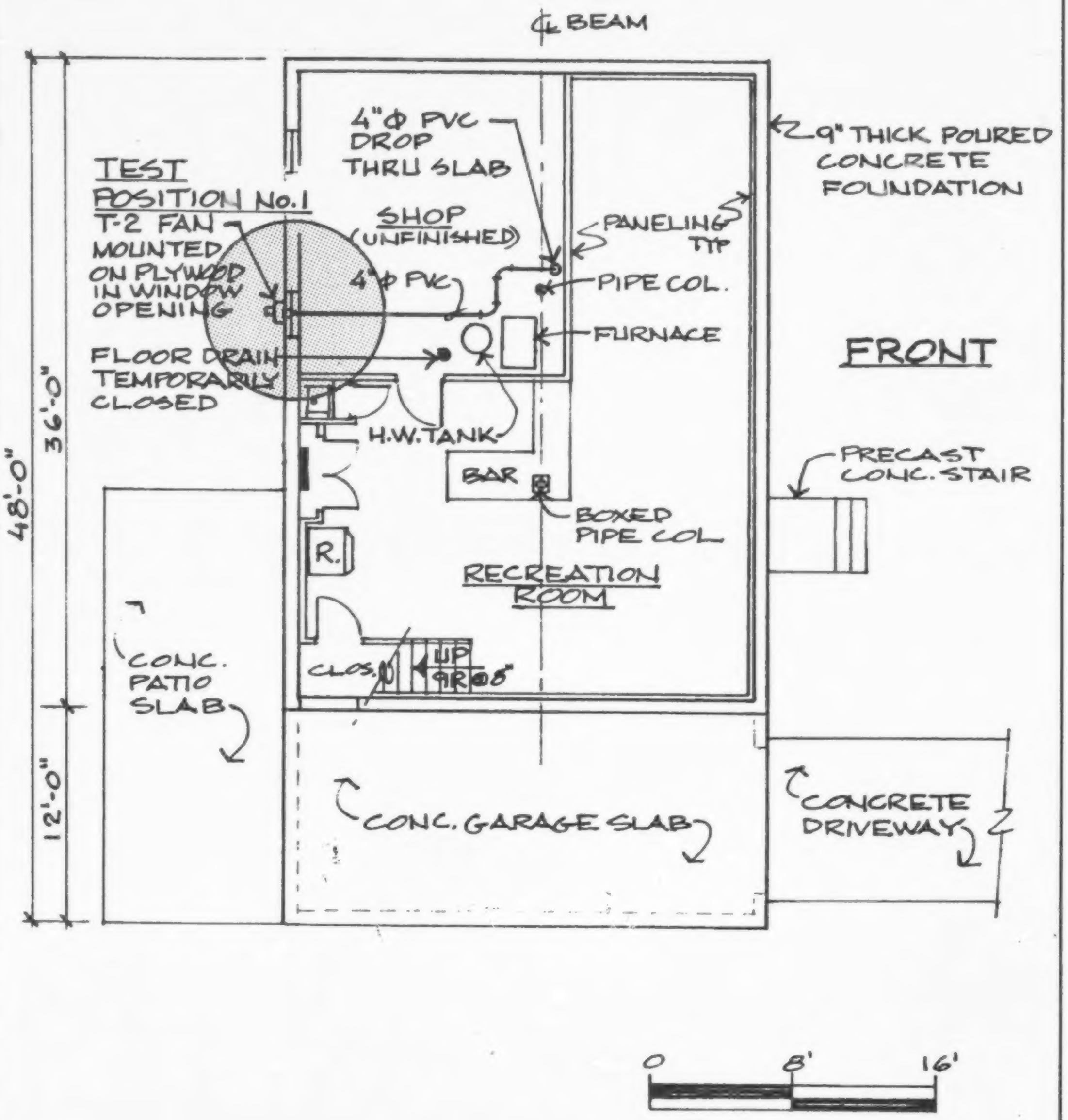
Date: 2/24/88

House Group: FULL BASEMENT

PHASE:

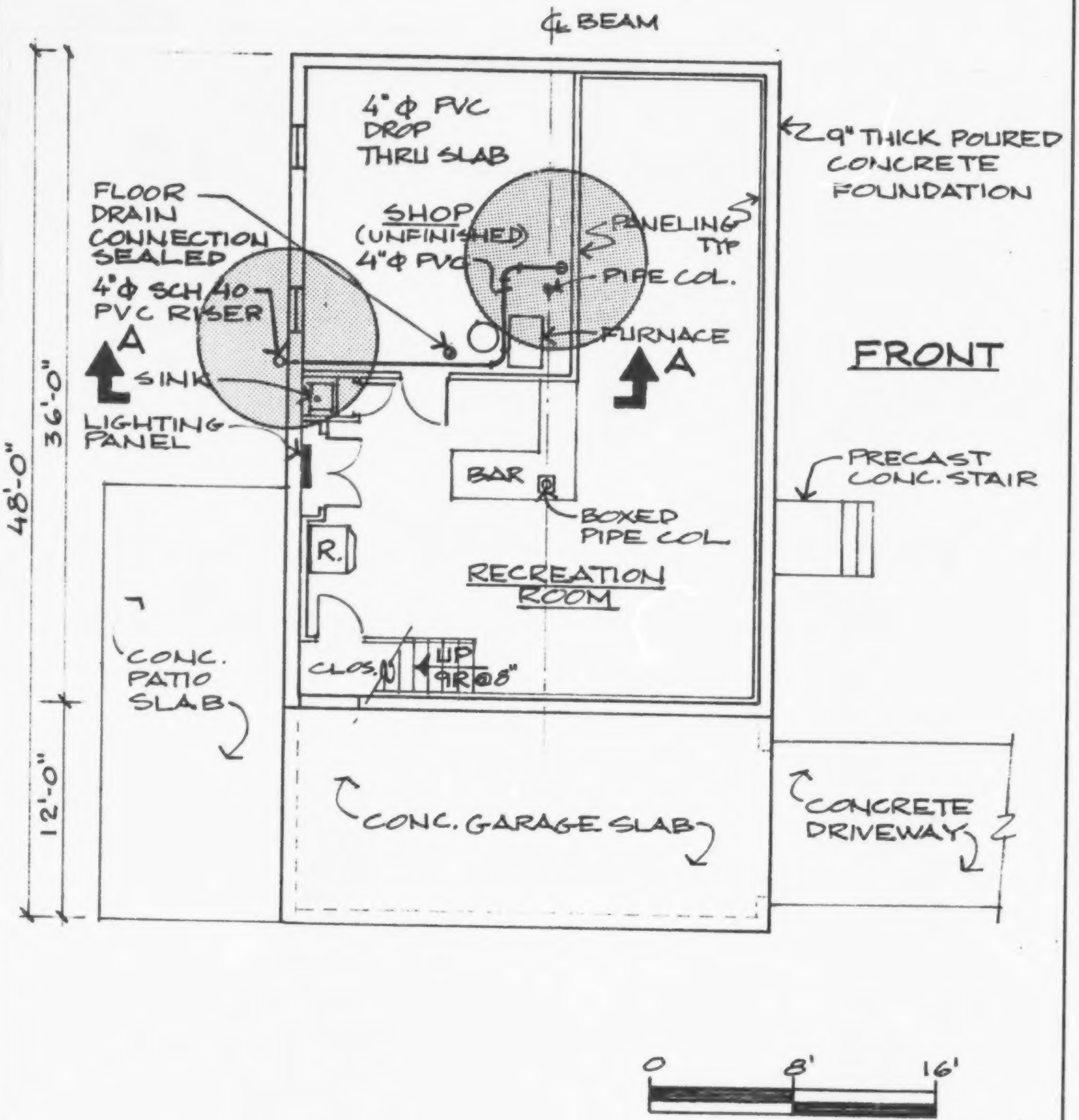


LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
GRADE LEVEL PLAN	Date: 2/24-88	45
House Group: FULL BASEMENT	PHASE:	



ACRES
Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON		**HOUSE NUMBER**
BASEMENT/FOUNDATION PLAN	Date: MAY 1988	45
Mitigation system: SUB-SLAB SUCTION	PHASE: TEST	



ACRES
Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON

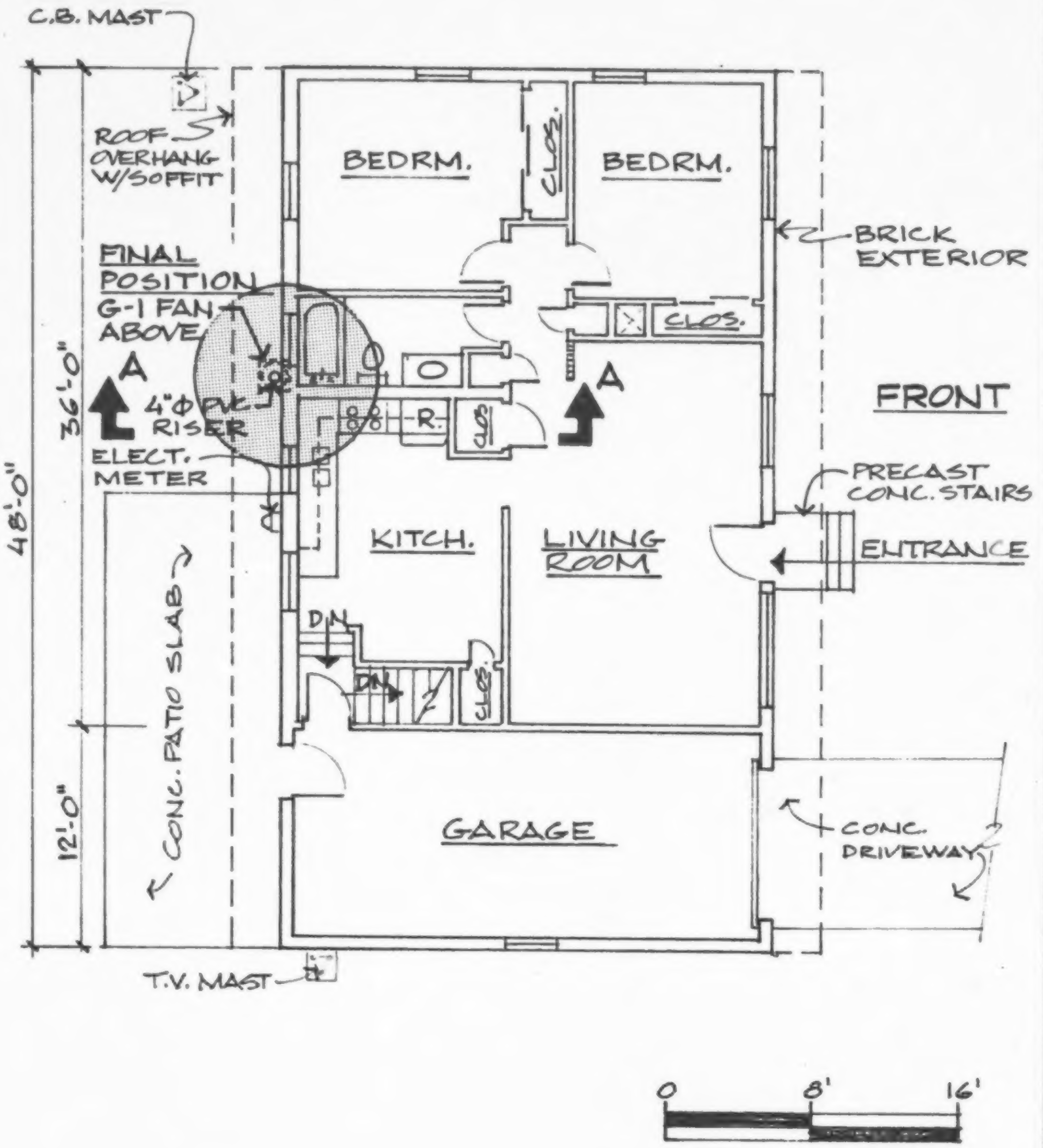
BASEMENT/FOUNDATION PLAN

Date: MAY 1988

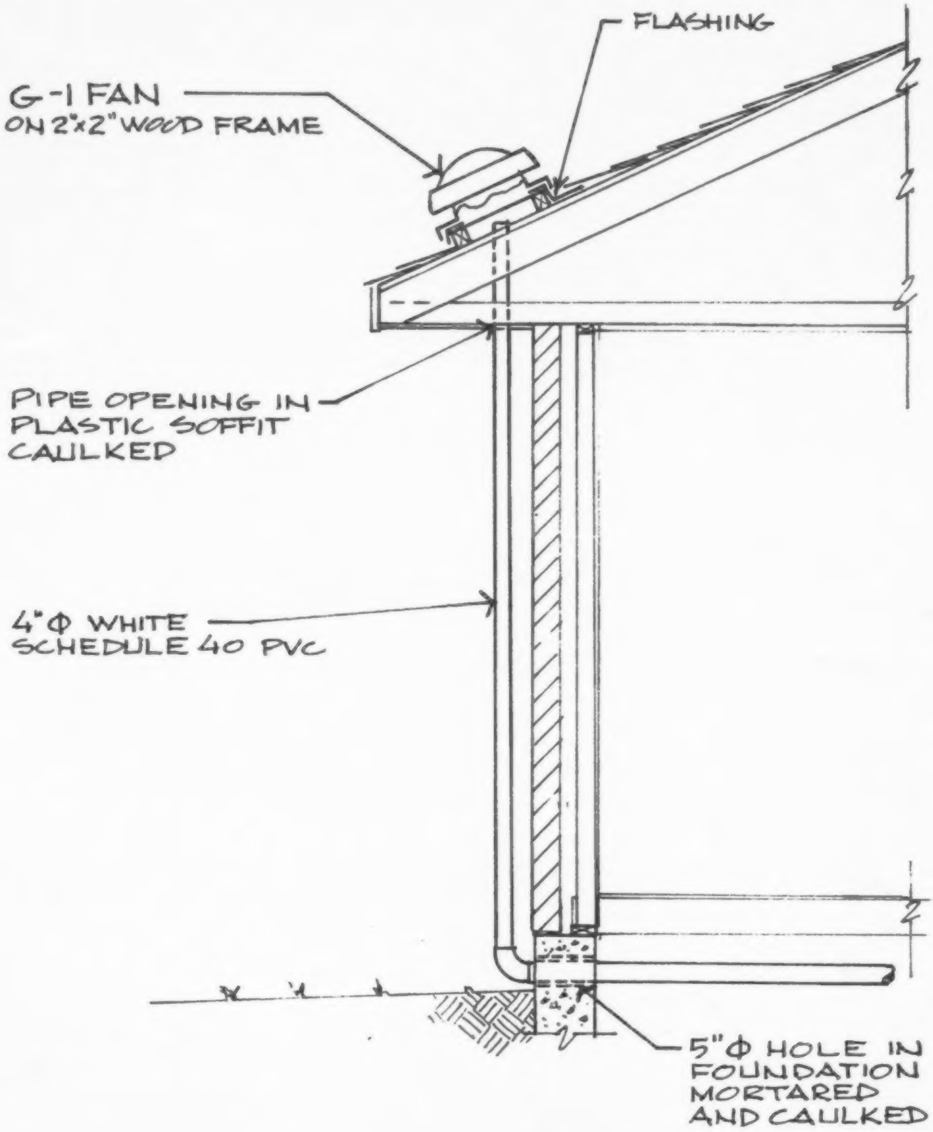
Mitigation system: SUB-SLAB SUCTION

PHASE: FINAL

HOUSE NUMBER 45



ACRES Acres International Corporation	**LOW COST REDUCTION OF INDOOR RADON**	**HOUSE NUMBER**
	GRADE LEVEL PLAN | Date: MAY 1988	45
	Mitigation system: SUB-SLAB SUCTION | PHASE: FINAL	



SECTION A-A
N.T.S.

ACRES Acres International Corporation	LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
	SECTIONS/DETAILS	Date: MAY 1988	45
	Mitigation system: SUB-SLAB SUCTION	PHASE: FINAL	

HOUSE 47

1 GENERAL DESCRIPTION

This small (100 m^2) slab-on-grade house with a detached garage was built in the late 1950's in a suburban subdivision just to the east of Kettering. The foundation wall is of poured concrete, the exterior walls are of metal siding. The floor in the kitchen and bathroom is covered with modern vinyl tile, the remainder is covered with fitted carpet, applied over the original tile. Heating is by a down-draft forced-air gas furnace with an air conditioning coil located centrally in a closet and clay heat distribution ducts running radially beneath the floor slab to clay register boxes. Slush concrete had been poured into the bottom of each box to close it, and the sub-slab gravel fill is visible in some boxes through gaps in the concrete. There is a large opening through the floor slab beneath the bath, accessible via a hinged panel in the sitting-room wall.

2 INVESTIGATION

In January 1988, a short-term continuous radon-monitor test conducted as part of the pre-selection process found radon concentrations in the living room ranged from 20 to 32 pCi/L, averaging 25.4 pCi/L over 40 hours.

In mid February 1988, the role of the sub-slab heating ducts in radon entry to the house was investigated by turning on the furnace fan to operate continuously. This would pressurize the ducts and so prevent the entry of soil gas into the house via the ducts. It would also pressurize the sub-slab gravel by leakage from the ducts, and so decrease the movement of soil gas and radon from the soil into the gravel. This had a significant effect on the radon concentration. With the fan cycling normally (on "automatic") for two days, radon concentrations in the house ranged from 24 to 35 pCi/L, averaging 30.1 pCi/L. Then, when the fan was set to continuous run, the concentration peaked to 40 pCi/L within 2 hours, and then fell slowly over the next 24 hours to about 10 pCi/L, averaging 14.5 pCi/L over a 31-hour period (Figure 47-2). The radon concentration started to rise immediately the fan was returned to "Auto" operation.

The pressure in the sub-slab gravel with the fan off was slightly higher (<1 Pa) than in the house, and air flows from soil to house were visualized with smoke. With the fan on, the pressure in the sub-slab gravel was 5 Pa higher than in the house, measured through a gap between the register box and the distribution duct with the grille removed. The pressure in the furnace plenum was 65 Pa. An air sample taken from beneath the floor slab at a register box before the fan was turned on was 520 pCi/L.

These results suggested that the initial effect of the fan was to force air with elevated radon content from beneath the slab into the house. There was a large opening in the slab beneath the bath about 500 by 600 mm, and so a second test was to fill this opening with expanding urethane foam to reduce the flow of air from the sub-slab fill. When the access panel was opened, the opening and most of the space around the bath was covered with loose mineral wool insulation and construction rubbish. Nearly 30 L was removed by hand to expose the gravel.

Despite this major reduction in open area, the radon supply into the house was not greatly affected. In February 1988, with the furnace fan cycling normally (on "Auto"), radon concentrations over the two days prior to closure ranged from 27 to 39 pCi/L averaging 32.8 pCi/L, and two days after closure the concentration varied from 17 to 32 pCi/L, averaging 25.2 pCi/L (Figure 47-3). A second run with the furnace fan operating continuously after closure gave a result similar to the previous run with the bath hole open; the radon concentration fell over a 24 hour period to range from 6 to 13 pCi/L, averaging 9.7 pCi/L. When the fan was turned back to "Auto", the concentrations started to rise immediately, reaching 20 pCi/L after about 36 hours.

These results suggested that there were other large connections to the sub-slab space besides the bath opening, probably the joint between the floor slab and the perimeter wall. This joint lies underneath the sole plate of the interior frame wall, and is not normally accessible or visible. The lack of effect of the closure was confirmed by a second run with the furnace fan on "Auto" (and with the bathtub opening closed) showed radon levels ranged from 16 to 40 pCi/L, averaging 22.9 pCi/L over 97 hours, essentially the same as the same mean as the first set of radon measurements after closure.

Additional sub-slab pressure distribution measurements were made by drilling two 12 mm holes through the floor slab, one near the furnace (A) and one near the front of the house (B). A probe down the holes found about 10 cm of gravel, with a layer of yielding material (clay?) beneath.

The furnace had not operated for a few hours as the weather was warm, and radon concentrations beneath the slab were very similar, 240 pCi/L at A, 200 pCi/L at B. With the furnace fan running, the pressure at hole A rose to 20 Pa. The hole was closed with putty, and after the fan had run for 5 minutes the concentration was remeasured at 20 pCi/L, showing clearly that the HVAC system did force low-radon air into parts of the sub-slab space.

The pressure at B was 9 Pa with the nearby register vent open, and increased to 12 Pa when the grille was closed. The pressure in the register box was about 8 Pa with the grille open, and 12 Pa with the grille closed. This register box has the clay pipe cemented in, and a continuous layer of concrete in the bottom of the box, so the variation in sub-slab pressurization must have been caused by leakage from the duct, not directly from the box.

The foam placed in the bath opening had expanded to completely fill the opening and was hard. A thin probe was inserted through the foam, and the pressure beneath the foam was 8 Pa.

A third hole (C) was drilled into the sub-slab space at the opposite end of the house through the solid concrete foundation wall from outside. When the fan operated, the pressure differential increased by about 5 Pa. Measurement was complicated by the variable wind pressure on the end of the building, which at times was 15 Pa lower than the sub-slab pressure. There was good communication between the house and the sub-slab space, for the pressure transient of several Pa caused by opening or closing a door was shown clearly on the gauge. The net DP across the house shell measured at the front door was about 1 Pa, with the house pressure lower.

In March 1988, a test hole was drilled into the soil at the side of the house to a depth of 1.8 m with a power auger. The top 30-50 cm was an organic loam, underlain by a 50 cm layer of moist coarse grained clay that was easily broken, followed by a sandy clay. At 1.3 m small limestone pebbles appeared in the clay. A capped 4" lightweight pipe was placed in the pipe to keep the hole open.

3 MITIGATION

The mitigation system chosen for demonstration at this house was sub-slab exhaust via the foundation wall. The installation was planned in two stages; a temporary system to check the effectiveness of the system, followed by a permanent installation.

In March 1988, hole C was enlarged to 10 cm diameter to install a temporary sub-slab suction via the foundation wall. A toilet flange was used as an adapter and a temporary fan-in-a-box was connected through flexible plastic hose. With the fan operating at maximum speed, radon concentrations in the house ranged from 0 to 3 pCi/L, averaging 1.1 pCi/L over 91 hours. When the fan was operating at "low" speed, concentrations rose slightly to range from 1 to 4 pCi/L, averaging 2.9 pCi/L over 83 hours. Clearly sub-slab suction was effective.

System measurements found that at high fan speed the flow rate was 23 L/s at a radon concentration of 150 pCi/L. With the fan running, the pressure at hole A rose from 0 to 17 Pa when the HVAC fan was switched on to continuous run. The pressure difference across the house shell varied between 2 and 7 Pa. At low fan speed the exhaust radon concentration was 65 pCi/L at a flow rate of 9 L/s with a suction of 110 Pa in the pipe.

The temporary fan was reversed to apply pressure to the sub-slab space. With the fan providing outside air at a flow rate of 11 L/s, radon levels in the house ranged from 3 to 29 pCi/L, averaging 16.0 pCi/L over 65 hours. This was a much poorer performance than achieved by sub-slab suction. Radon concentrations in the ground pipe at that time were measured at 5 and 7 pCi/L on two different days, indicating that the pressurization caused by the fan was not driving soil gas and radon into the pipe.

In April 1988, the system was returned to sub-slab suction. With the fan operating at maximum suction, radon concentrations in the house ranged from 0 to 2 pCi/L, averaging 0.8 pCi/L over 24 hours with the HVAC fan on "Auto", and ranged from 0 to 2 pCi/L, averaging 1.1 pCi/L over 40 hours with the HVAC fan running continuously. These results are essentially identical, and indicate operating the HVAC fan in this house does not affect the performance of the sub-slab suction.

4 FINAL INSTALLATION

A second hole was cored through the foundation wall at the end of the house close to the first fan hole (C) to install a permanent fan. When the core was removed, it was found that there was a clay register box directly in front of the opening. This box was concealed from view in the house by an ornamental false fireplace, and had been had been closed off. When the gravel was cleaned out from the opening, it was also found that there was a layer of fibre-glass insulation beneath the floor slab, that had not been observed at the edge of the floor slab beneath the bath.

In April 1988, a temporary fan system was installed to test sub-slab suction at the second location. Radon levels ranged from 0 to 2 pCi/L, averaging 0.7 pCi/L over 42 hours, with the fan delivering 32 L/s at 295 Pa. At start-up time the radon in the ground riser measured 370 pCi/L. After two days of running, the radon in the ground riser had fallen to 2 pCi/L and radon in the fan effluent measured 50 pCi/L.

Following this satisfactory result, in May 1988 a small excavation was made beneath the hole to give clearance for a T-2 fan mounted on a panel of marine plywood screwed and caulked to the wall over the hole. A basement window-well was placed in the excavation to maintain clearance. Hole C was filled with cement.

5 OTHER MEASUREMENTS

The 1987 charcoal canister test gave a value of 20.5 pCi/L in the furnace closet. In January 1988, a short term continuous radon monitor test found radon concentrations in the living room ranged from 20 to 32 pCi/L, averaging 25.4 pCi/L.

Pre-mitigation alpha-track measurements over the period December 1987 to February 1988 gave average radon concentrations of 22.9 pCi/L in the kitchen and 24.1 pCi/L in the bedroom.

Post-mitigation alpha-track measurements over the period May to August 1988 gave an average radon concentration of 2.1 pCi/L in the living area.

The radiation field in the house ranged from 3 to 5 μR/h over the entire floor slab. The field over the site outside the house ranged from 5 to 7 μR/h, averaging 6 μR/h.

MEASUREMENTS SUMMARY FOR HOUSE 47

PYLON AB-5 HOURLY MONITORING

MITIGATION SYSTEM	TEST DATE	TEST STATUS	RADON (pCi/L)		MONITOR DURATION	FIG.
			RANGE	MEAN		
pre-selection	01/88		20-32	25.4	40 hrs	47-1
sub-slab pressurized using HVAC fan	02/88	HVAC on auto	24-35	30.1	47 hrs	47-2
		HVAC operating continuously	10-20	14.5	31 hrs	47-2
bath-tub opening foamed (HVAC on auto)	02/88	before	27-39	32.8	44 hrs	47-3
		after	17-32	25.2	44 hrs	47-3
sub-slab pressurized (HVAC), after foaming	02/88	HVAC on continuously	6-13	9.7	43 hrs	47-4
		HVAC on auto	13-22	15.2	41 hrs	47-4
	03/88	auto	16-40	22.9	97 hrs	47-5
sub-slab suction	03/88	DPmax	0- 3	1.1	91 hrs	47-6
	03/88	DPlow	1- 4	2.9	83 hrs	47-7
sub-slab pressured	03/88	DPlow	3-29	16.0	65 hrs	47-8
sub-slab suction	04/88	DPmax;auto	0-2	0.8	24 hrs	47-9
		DPmax; cont.	0-2	1.1	40 hrs	47-9
sub-slab suction (new location)	04/88	DPmax	0-2	0.7	42 hrs	47-10

Average pre-mitigation Pylon results (presented in Tables IX, X, XI and 3):

Weighted average of Figure 47-1, HVAC-auto portion of Figure 47-2, and before-foaming portion of Figure 47-3 (131 hours total) = 29.6 pCi/L.

Average post-mitigation Pylon results:

furnace fan on continuously (Table IX) — Fig. 47-2 (31 hr) = 14.5 pCi/L.
bathtub opening closed — Fig. 47-3 and HVAC-auto portion of Fig. 47-4 (85 hr) = 20.4 pCi/L.
furnace fan on after tub closure (Table IX) — Fig. 47-4 (43 hr) = 9.7 pCi/L.
sub slab suction, fan at DPmax (Table X) — Figs. 47-6, 47-9 (HVAC auto) and 47-10 (157 hours total) = 0.9 pCi/L.

SYSTEMS MEASUREMENTS

PHASE	MITIGATION SYSTEM	TEST DATE	MEASUREMENTS			COMMENT
			SUCTION (Pa)	FLOW (L/s)	RADON (pCi/L)	
	pre-mitigation	02/88	-<1*			natural DP across slab (register)
						before foaming
1	bath-tub opening foamed	02/88	-5		520	through register
			-66			through plenum
						after foaming
			-6			through register
			-64			through plenum
1	sub-slab pressurized using HVAC fan	03/88	-61			plenum
			-20		240	hole A;near plenum
					20	hole A;after 5 min.
			-9		200	hole B; near open register
			-12			hole B; reg. closed
			-8			reg. box;grille open
			-12			reg. box;grille closed
			-5			hole C; through foundation wall
			-1			across house shell
1	sub-slab suction	03/88	320	23	150	at fan; DPmax
			0			hole A; HVAC off
			17			hole A; HVAC cont
			2-7			across house shell
		03/88	110	9	65	at fan; DPlow
1	sub-slab pressured	03/88	-85-100*	11		at fan; DPlow
					5	ground riser
					7	ground riser
1	sub-slab suction (new location)	04/88	295	32		at fan; DPmax
					370	ground riser
		04/88			50	at fan;after 2 days
					2	ground riser;ditto

* "Negative suction" denotes pressurization relative to house.

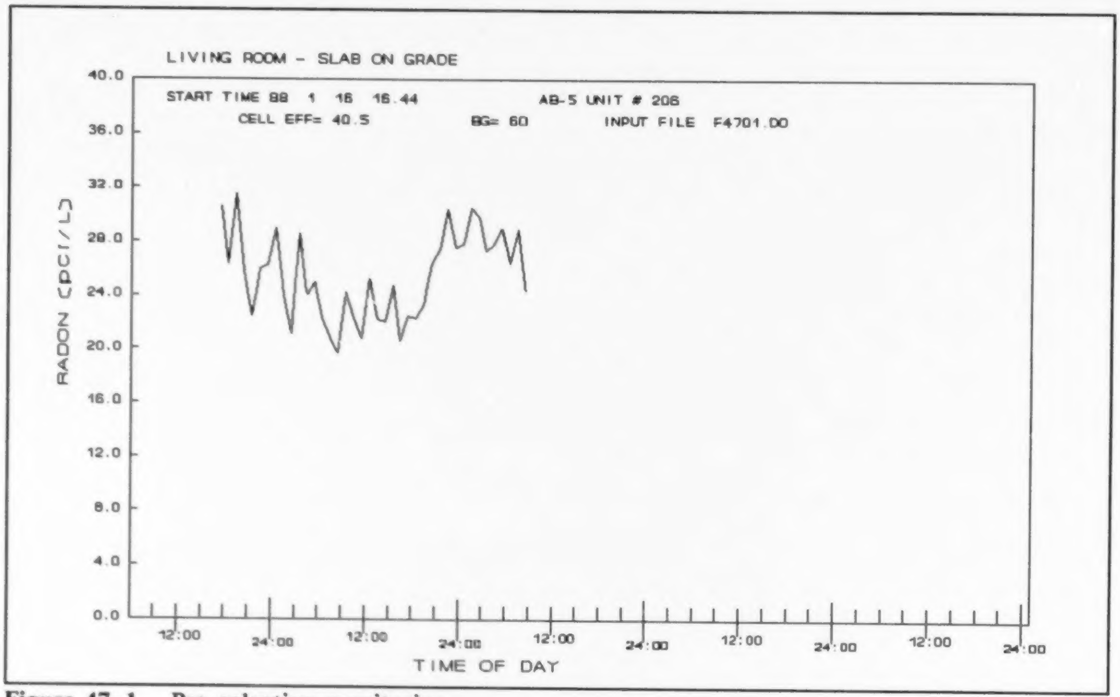


Figure 47-1. Pre-selection monitoring

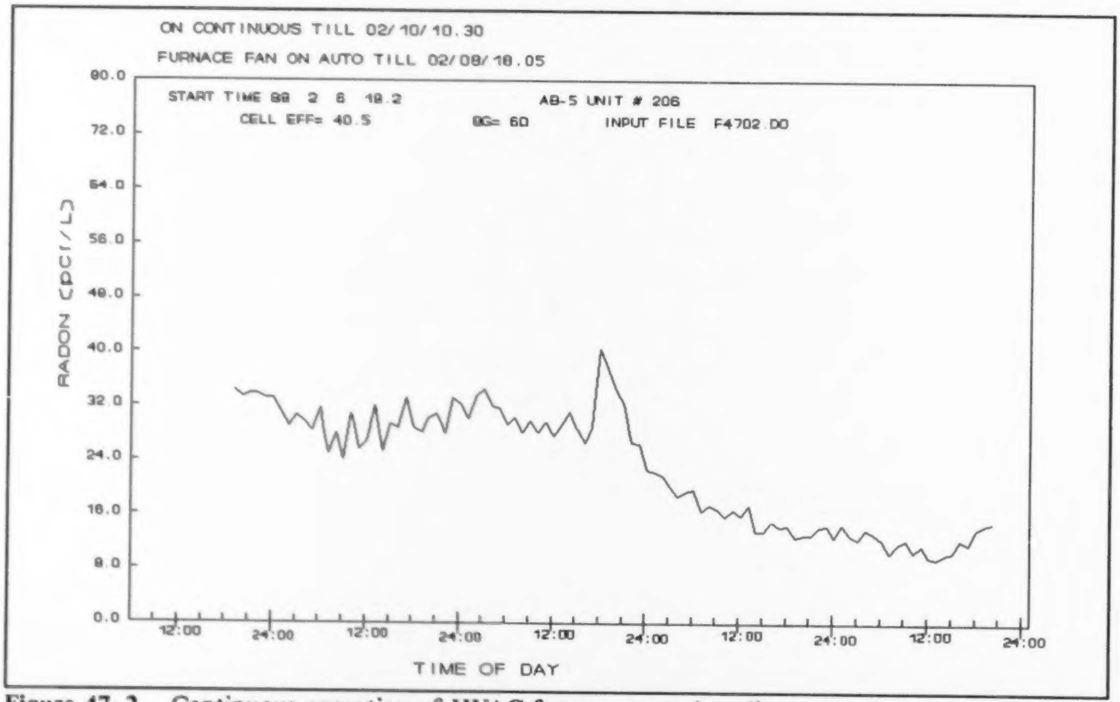


Figure 47-2. Continuous operation of HVAC fan, vs. normal cycling

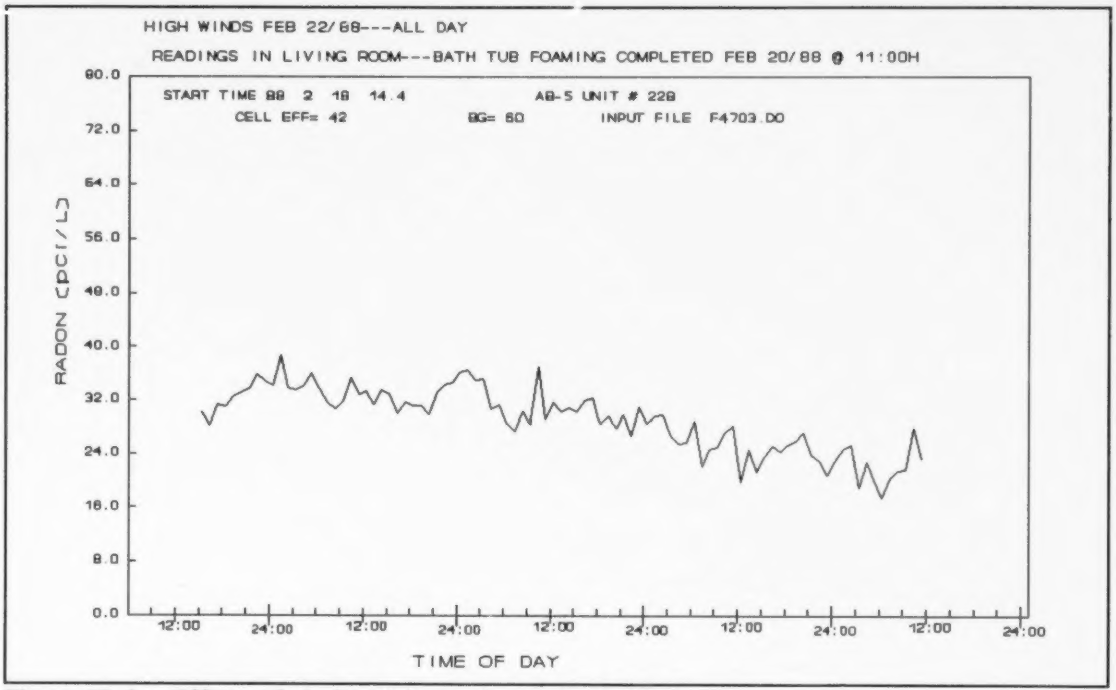


Figure 47-3. Effects of closing slab opening under bathtub

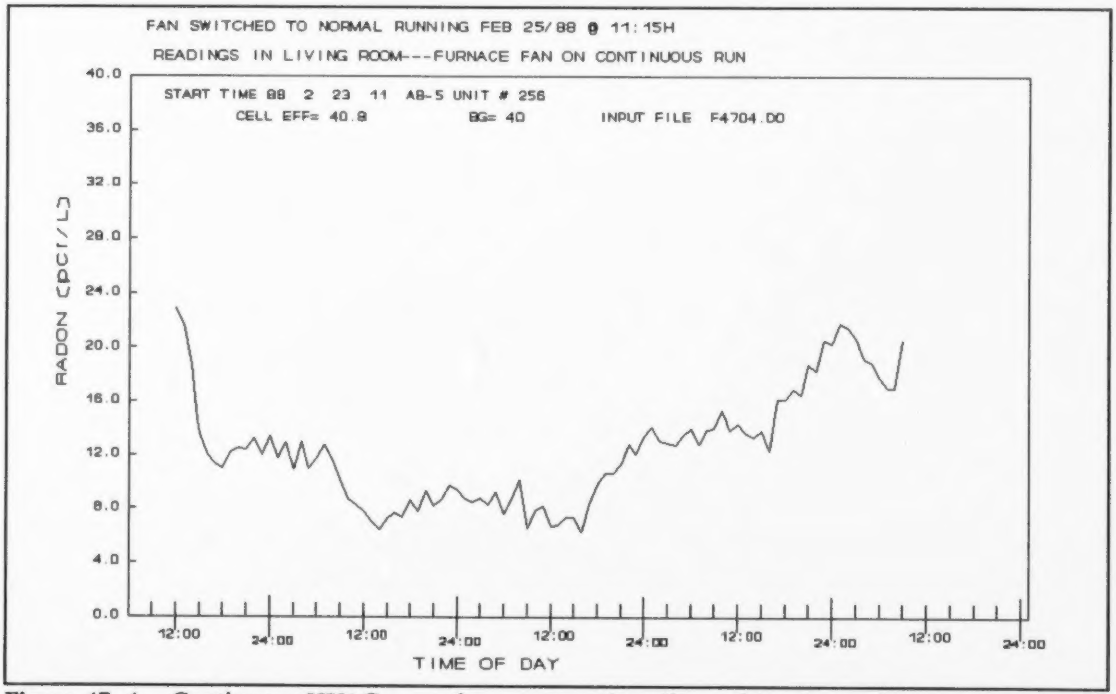


Figure 47-4. Continuous HVAC operation vs. normal cycling, with tub opening closed

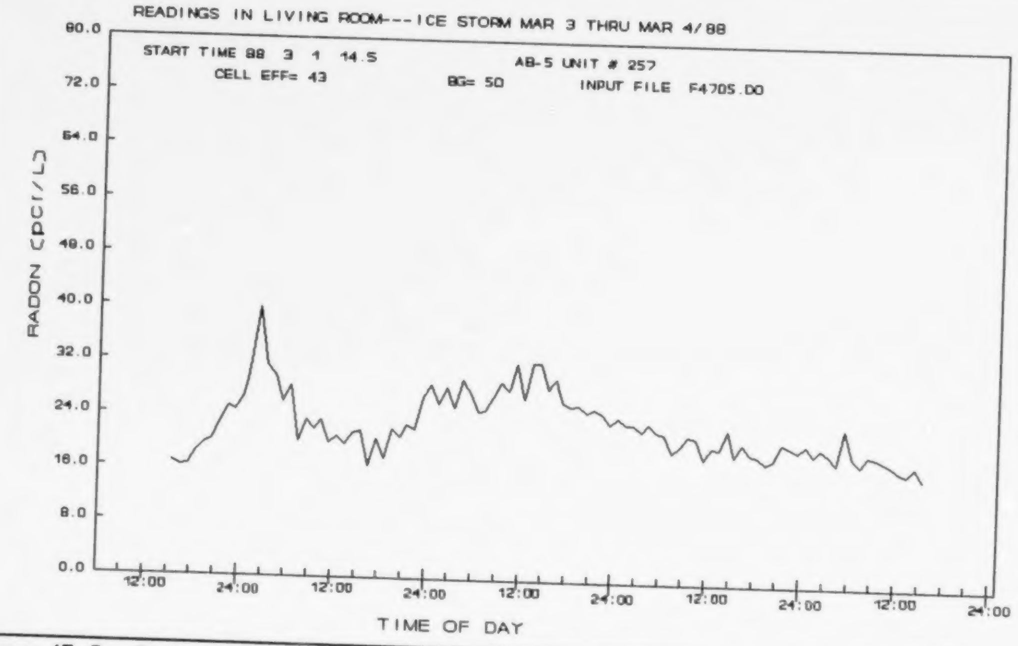


Figure 47-5. Bathtub opening closed, HVAC cycling normally

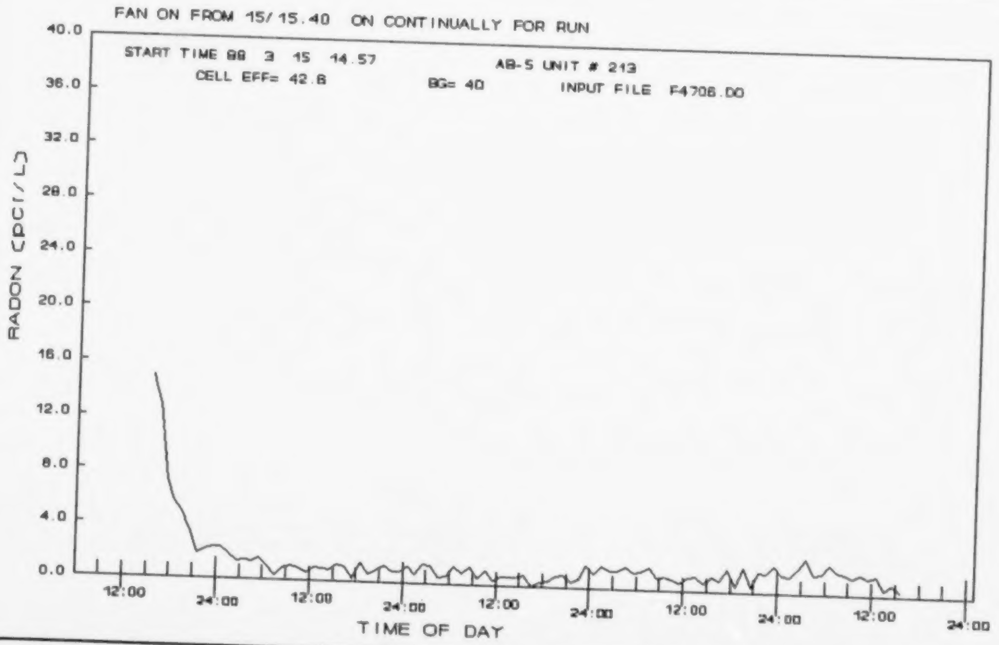


Figure 47-6. Sub-slab suction with exterior suction point, mitigation fan at DPmax

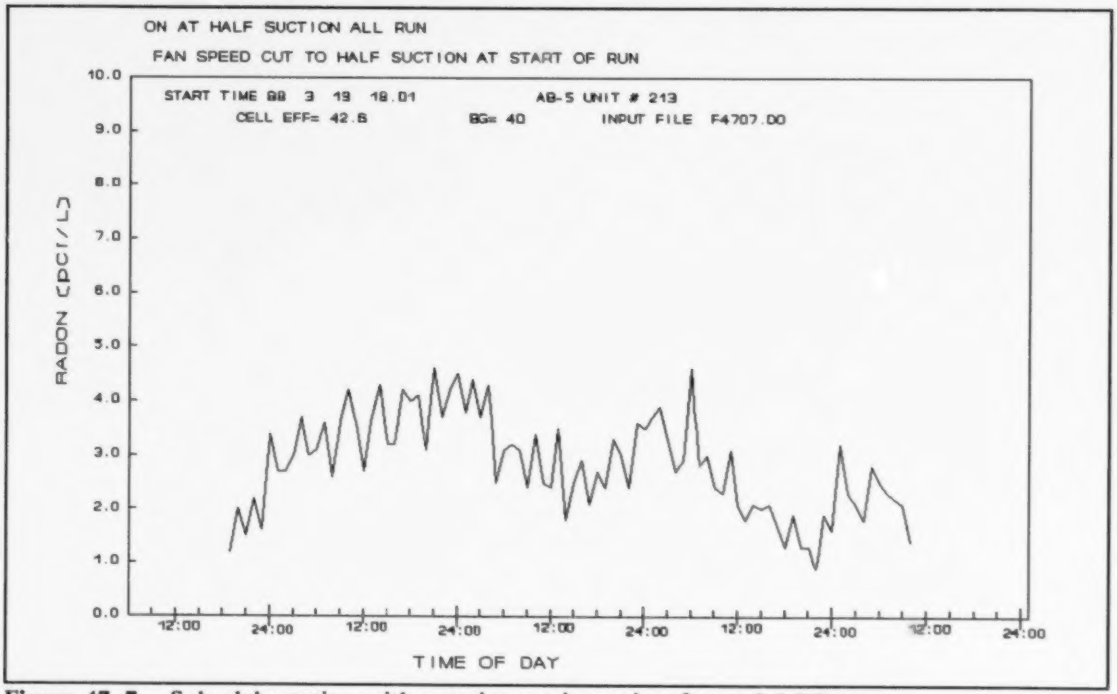


Figure 47-7. Sub-slab suction with exterior suction point, fan at 0.5 DPmax

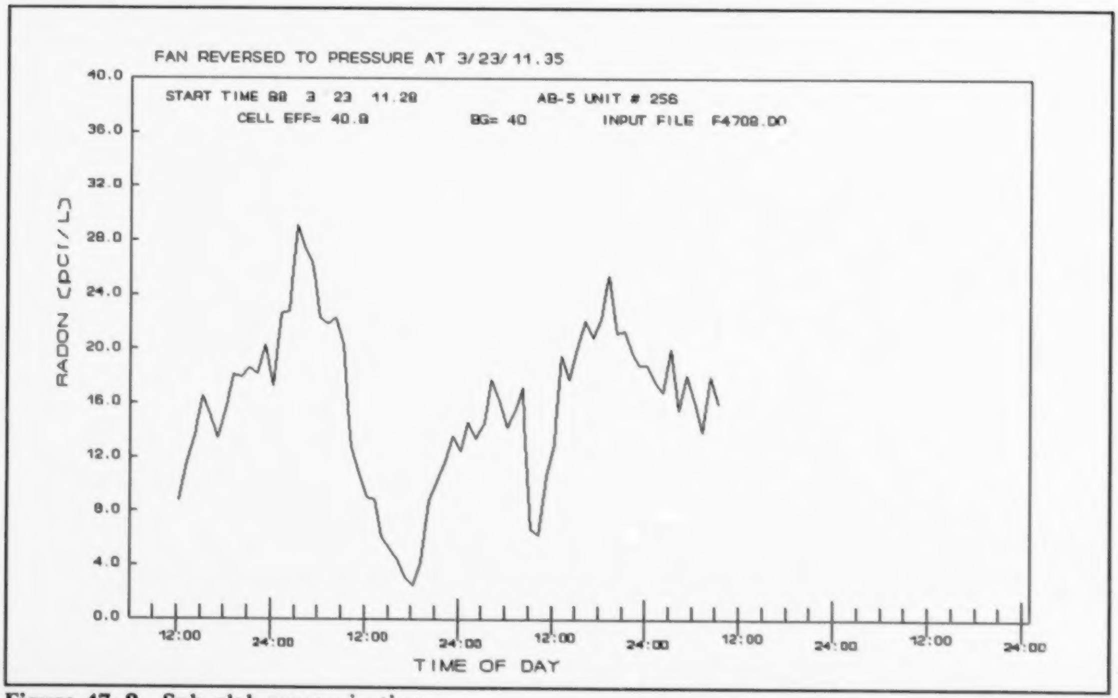


Figure 47-8. Sub-slab pressurization

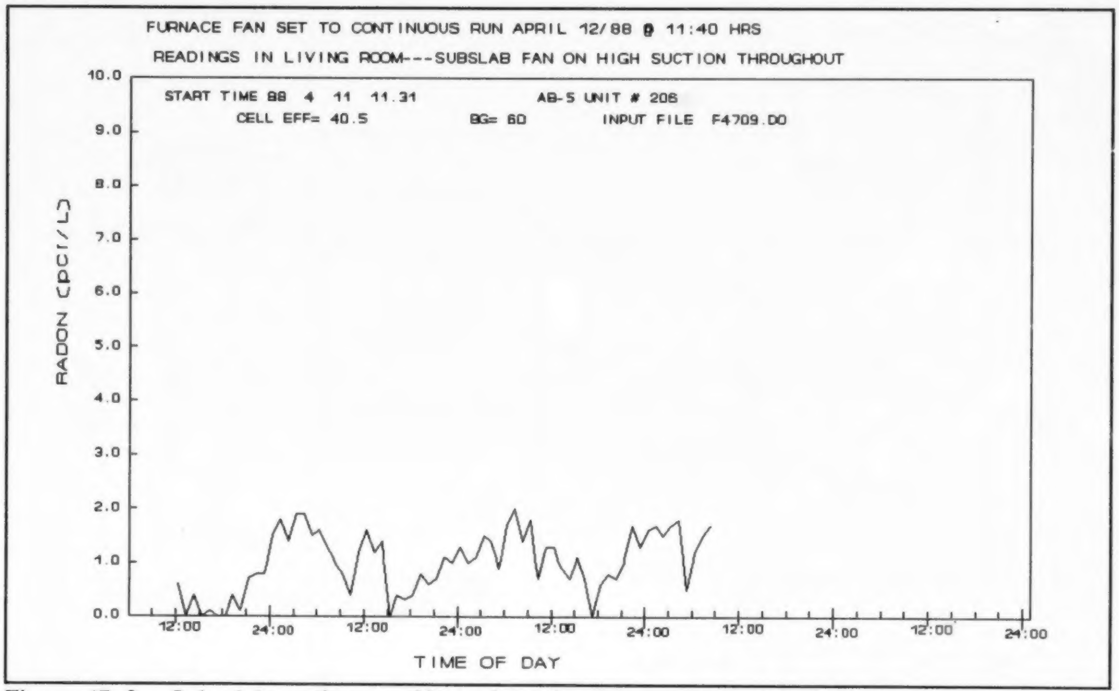


Figure 47-9. Sub-slab suction -- effect of continuous operation of HVAC fan

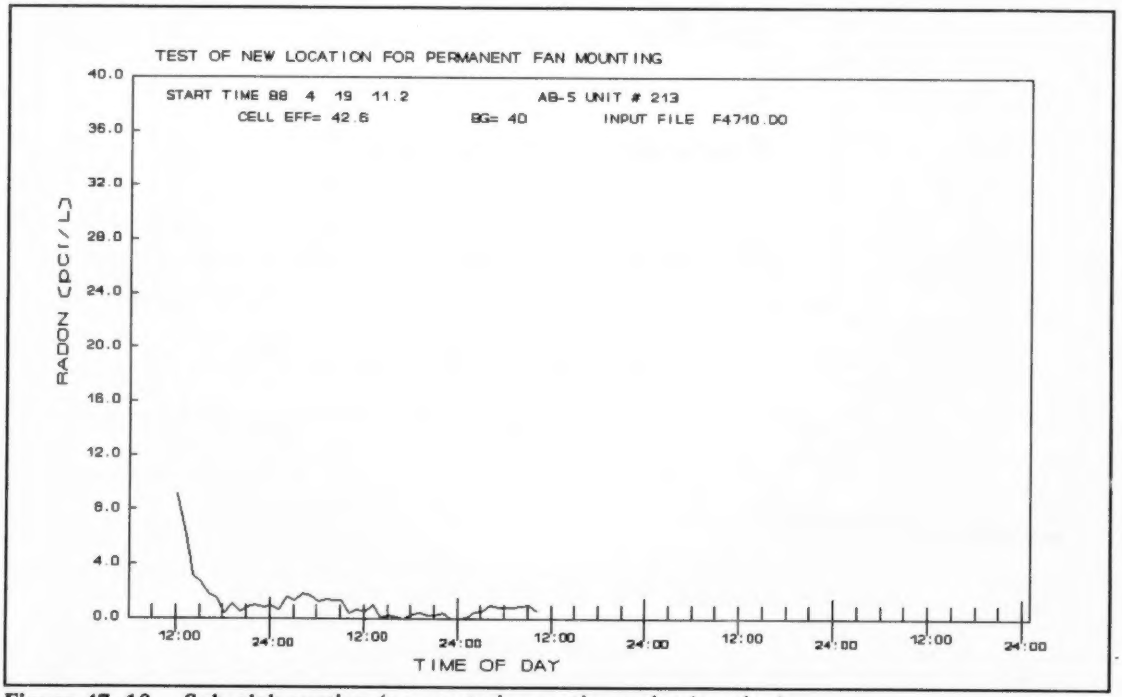
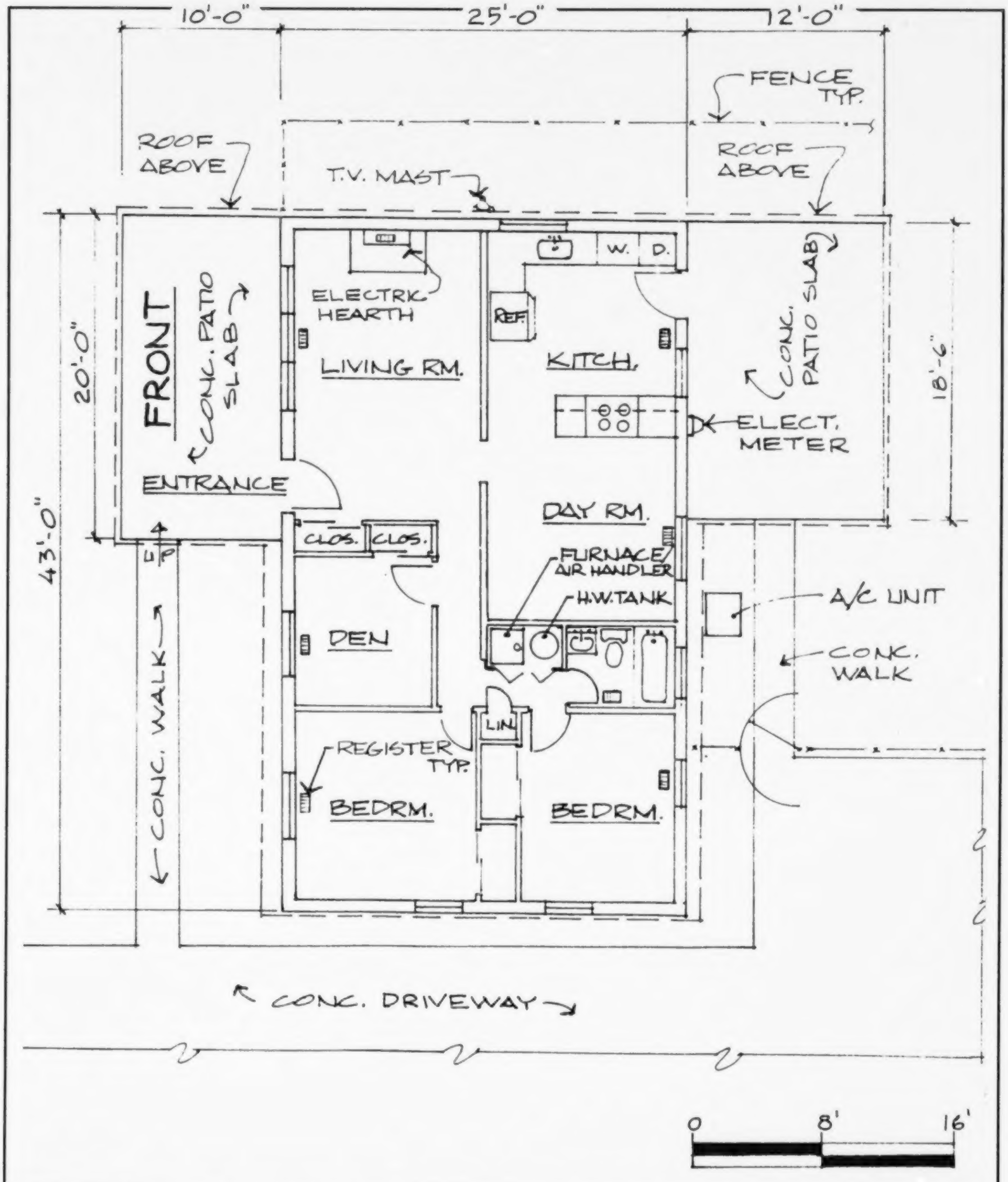


Figure 47-10. Sub-slab suction (new exterior suction point location)



ACRES
Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON

HOUSE NUMBER

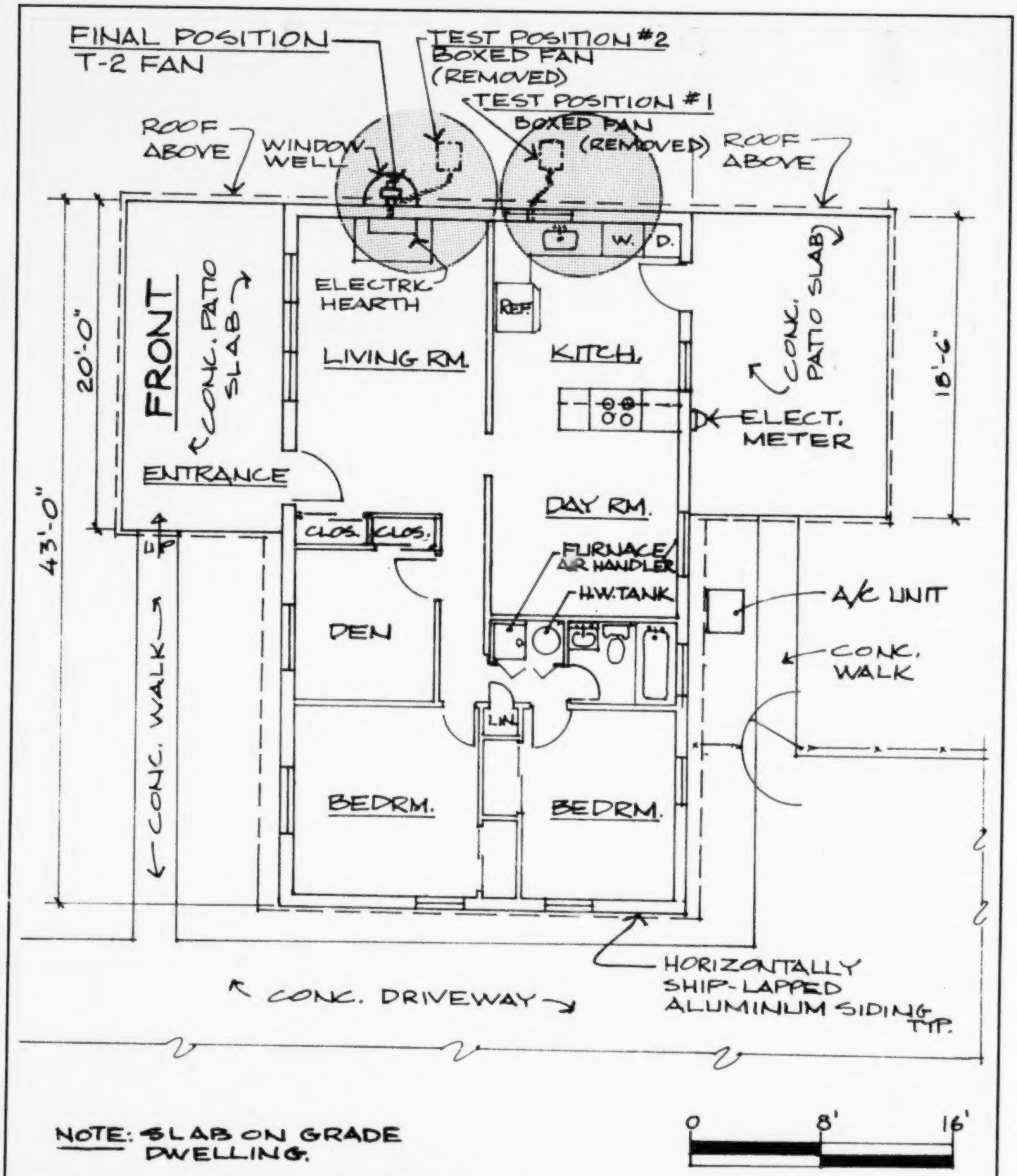
GRADE LEVEL PLAN

Date: 2/22/88

47

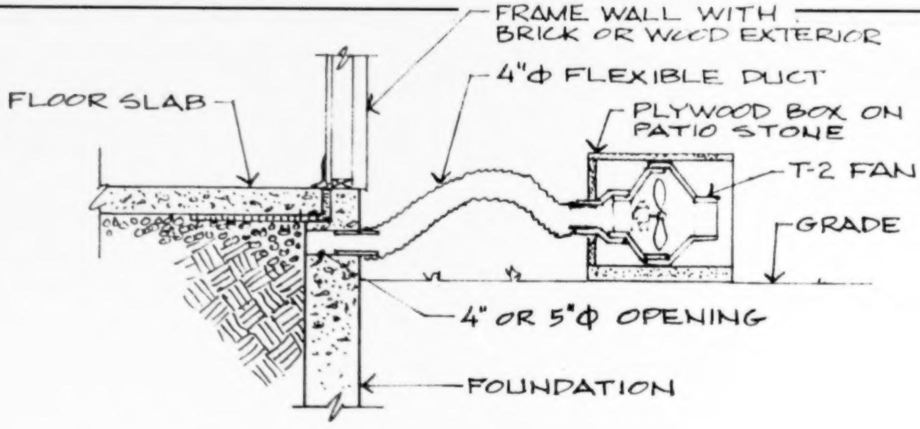
House Group: **SLAB ON GRADE**

PHASE:



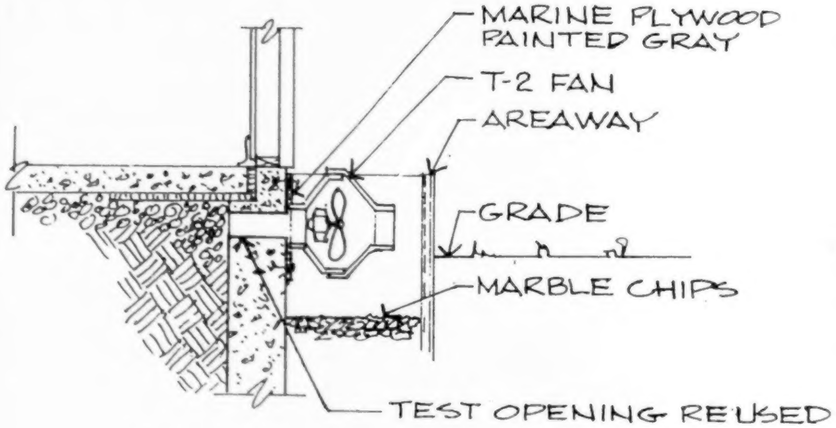
NOTE: SLAB ON GRADE DWELLING.

ACRES Acres International Corporation	LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
	GRADE LEVEL PLAN	Date: MAY 1988	47
	Mitigation system: SUB-SLAB SUCTION	PHASE: TEST AND FINAL	



TEST SYSTEM

N.T.S.



FINAL POSITION

N.T.S.

ACRES
Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON		HOUSE NUMBER
SECTIONS/DETAILS	Date: MAY 1988	47
Mitigation system: SUB-SLAB SUCTION	PHASE: TEST AND FINAL	

HOUSE 49

1 GENERAL DESCRIPTION

This small (110 m^2) single-story basement house with an attached garage was built on a hillside in the early 1970's in a suburban subdivision in the north of Bellbrook. The foundation walls are of poured concrete. The exterior walls are brick but for the gable end and eaves which are of siding. The site slopes steeply to the rear of the house, and there is a sliding-door walkout from the basement, and a separate earth-floored storage room accessible only from outside the house. The basement is unfinished, and there are a few wall cracks and extensive floor cracks, in addition to a large (3 mm) wall/floor joint. The basement slab is penetrated by water lines, the sanitary stack and a floor drain which is water-trapped. Heating is by an upflow forced-air gas furnace with air conditioning centrally located in the basement with metal heat distribution ducts running along the ceiling for the length of the ceiling.

2 INVESTIGATION

In January 1988 a short-term continuous radon-monitor survey as part of the pre-selection process found concentrations in the basement ranged from 7 to 12 pCi/L, averaging 8.7 pCi/L over 47 hours.

In February 1988, a pre-selection investigation of the radon contribution from the earthen-floored storage room was conducted. Radon monitors were placed in the basement and the upstairs living area, directly over the storage room. When the storage room door was closed, the basement radon concentration ranged from 5 to 8 pCi/L, averaging 6.1 pCi/L over a 49-hour period, and the living area radon concentration ranged from 4 to 7 pCi/L, averaging 5.1 pCi/L. When the storage room door was open, effectively reducing the radon concentration in the storage room to zero, the basement radon concentration ranged from 3 to 7 pCi/L, averaging 5.6 pCi/L over a 49-hour period, while the radon concentration upstairs ranged from 4 to 7 pCi/L, averaging 5.1 pCi/L. Clearly no significant change in radon concentration resulted from opening the door to the storage room, suggesting that the supply into the house from the earthen floor was negligible.

During the second week of March 1988, sub-slab communication was investigated by drilling a 30 mm hole in a central location, near the bottom of the basement stairs, a 12 mm hole at a distance of 30 cm away, and one 12 mm hole in two corners of the basement, approximately 6 m away. Undisturbed sub-slab radon samples of 950 and 1200 pCi/L were obtained at the large hole and the small adjacent hole, while basement air measured 4 pCi/L by a grab sample.

An industrial vacuum cleaner was used to both pressurize and then exhaust air from the sub-slab space via the large hole. Pressure measurements and smoke tests were conducted at the other holes. Smoke tests were also conducted at the perimeter joint, wall and floor cracks, and the drain and pipe penetrations. Although a pressure of 980 Pa was established at the 30 mm hole, and 150 Pa at the adjacent 12 mm hole, there was no measurable pressure (<1 Pa) at the remote holes. Similar results were obtained at a suction of 860 Pa. However, the smoke tests showed clear evidence, particularly on suction, air flow into the sub-slab space at all holes, the perimeter joint, the drain and pipe penetrations, and the junctions of floor cracks, but not at wall cracks.

3 MITIGATION

As this basement was completely unfinished, had solid concrete walls and the wall/floor joint was accessible, the mitigation system chosen for demonstration was caulking of the open joints in the basement.

A "sagging" polyurethane caulk (Dymonic) had been selected for use at this house, but it was reported other projects had good results with flowable urethane caulk, and so it was decided to test the flowable caulk (Vulkem) first. The perimeter wall/floor joint was prepared for caulking. Concrete protrusions were chipped off the edge of the floor slab to allow the nose of the caulking gun to traverse the joint smoothly. The area was then vacuumed, wire-brushed and vacuumed again before final cleaning with a damp sponge and a solvent. A bead of Vulkem flowable caulk was placed along the wall/floor joint. It was hoped that the viscosity would be high enough for the caulk to set before the material all flowed down into the wall/floor joint. Two and three applications of caulk were made at different sections of the joint, but in all instances the caulk flowed down the crack. The next day, suction was applied to the sub-slab space, and smoke tests found that the caulk had not filled the wall/floor joint, for air was drawn down into the joint.

A second attempt was made to close the wall/floor joint with the flowable caulk. The wall surface just above the wall/floor joint was wire-brushed, vacuumed and wiped, and then the caulk was placed on the wall in a thick bead and allowed to flow down the wall to cover the joint. The caulk spread out onto the floor, but still ran down the wall/floor joint, leaving openings in the caulk. Openings in the floor near the french doors were filled with rapid hardening cement.

Before the Vulkem caulk was applied, basement radon concentrations ranged from 3 to 7 pCi/L and averaged 5.8 pCi/L over 16 hours. After the caulking, basement radon concentrations ranged from 4 to 8 pCi/L and averaged 5.6 pCi/L over 63 hours (Figure 49-3), an insignificant difference.

A few days later, selected portions of the perimeter joint were caulked with a single-part sagging urethane caulk, Tremco Dymonic, applied over the Vulkem. After one day for setting, the caulk was inspected, and appeared visually to be adhering well to the set Vulkem caulk. The Dymonic remained in place, with little or no sinking, except where the joint was very wide.

In mid-March 1988, the entire perimeter joint area was cleaned and caulked with Dymonic caulk. The flowable caulk which had spread out onto the floor was removed by cutting through the layer of caulk and scraping off the excess material. This was difficult for the caulk adhered very well to the concrete. The surface was cleaned by wiping with a damp sponge and left to dry. A large bead of Dymonic caulk was placed over the wall/floor joint. Caulk was placed around all floor penetrations. Suction tests were conducted using the vacuum cleaner (2000 Pa) and a smoke pencil. Leakage was found only in those few places where the bead of caulk was not large enough to touch the concrete on both sides of the joint. These areas were re-caulked. Following this work, basement radon concentrations ranged from 3 to 5 pCi/L and averaged 4.1 pCi/L over 94 hours (Figure 49-4).

The caulking was tested by taping polyethylene sheet collectors over 14 sections of wall/floor joint and 4 areas with floor cracks. The next day, when the basement radon concentration was 4 pCi/L according to a grab sample, the wall/floor joint collectors had radon concentrations ranging from 70 to 720 pCi/L while the crack collectors had concentrations ranging from 40 to 290 pCi/L. These results indicated that soil-gas and radon was leaking around the caulk despite the considerable caulking effort, and that the floor cracks were not as large a radon entry route as the wall/floor joint.

In mid-April 1988, a second bead of Dymonic caulk was applied over the top of the first to ensure that the bead of caulk was continuous. The wall, floor, and in-situ caulk were cleaned by vacuuming, sponging with clean water. After the area was dry, any surface dust was removed by a jet of air. To improve adhesion to the concrete surfaces, the manufacturer's primer was painted onto the contact areas, and let dry before applying the caulk. Dymonic caulk was then applied to the entire wall/floor joint and tooled to ensure that it was forced into contact with the wall and the floor. However, no significant change took place in basement radon concentrations, which ranged from 3 to 7 pCi/L and averaged 4.4 pCi/L over 66 hours (Figure 49-5). As radon concentrations in the basement were low, no further work was planned in this house.

4 OTHER MEASUREMENTS

The 1987 charcoal canister test gave a radon value of 9.0 pCi/L in the basement. A short-term radon-monitor survey in January 1988 found concentrations in the basement ranged from 7 to 12 pCi/L, averaging 8.7 pCi/L.

Pre-mitigation alpha-track measurements over the period December 1987 to February 1988 gave average radon concentrations of 4.0 pCi/L in the living area and 4.8 pCi/L in the basement.

Post-mitigation alpha-track measurements over the period May to August 1988 gave average radon concentrations of 1.3 pCi/L in the living area and 3.6 pCi/L in the basement.

The gamma radiation field in the basement ranged from 3 to 5 μR/h, averaging 4 μR/h, whereas the gamma field over the site ranged from 5 to 8 μR/h, averaging 7 μR/h.

MEASUREMENTS SUMMARY FOR HOUSE 49

PYLON AB-5 HOURLY MONITORING

MITIGATION SYSTEM	TEST DATE	TEST STATUS	RADON (pCi/L) RANGE	RADON (pCi/L) MEAN	DURATION/ LOCATION	FIG.
pre-selection[*]	01/88		7-12	8.7	47 hrs; B[+]	
pre-mitigation (storage room door open/closed)	02/88	door closed	5- 8	6.1	49 hrs; B	49-2
		door open	3- 7	5.6	49 hrs; B	49-2
		door closed	4- 7	5.1	49 hrs; LR[+]	49-1
		door open	4- 7	5.1	49 hrs; LR	49-1
closure of wall/ floor joint etc.	03/88	before caulk	3- 7	5.8	16 hrs; B	49-3
		Vulkem caulk	4- 8	5.6	63 hrs; B	49-3
	03/88	Dymonic caulk	3- 5	4.1	94 hrs; B	49-4
	04/88	primer+wider Dymonic bead	3- 7	4.4	66 hrs; B	49-5

[*] RAPCA femto-TECH R210F used

[+] B=Basement; LR=Living Room

Average pre-mitigation Pylon results (presented in Tables XVI and 3):

Basement

Weighted average of Figures 49-2 and pre-caulking portion of 49-3 (161 hours total) = 5.8 pCi/L.

Average post-mitigation Pylon results (slab closure, presented in Table XVI):

Basement

Average of Figure 49-5 (66 hours) = 4.4 pCi/L.

SYSTEMS MEASUREMENTS

PHASE	MITIGATION SYSTEM	TEST DATE	MEASUREMENTS			COMMENT
			SUCTION (Pa)	FLOW (L/s)	RADON (pCi/L)	
1	pre-mitigation	03/88	980		950	pressure at slab
			150		1200	at hole 1
			0			at hole 2
			0			at hole 3
					4	basement air
			860			suction at slab
1	wall/floor caulked with Vulkem	03/88	2000			suction at slab
			2			at hole 2
			0			at hole 3
1	wall/floor caulked with Dymonic	03/88			4	basement air
					70	bag A; wall/floor
					160	bag B; wall/floor
					550	bag C; wall/floor
					720	bag D; wall/floor
					170	bag E; wall/floor
					380	bag F; wall/floor
					400	bag G; wall/floor
					130	bag H; wall/floor
					80	bag I; wall/floor
					180	bag J; wall/floor
					270	bag K; wall/floor
					250	bag L; wall/floor
					710	bag M; wall/floor
					450	bag N; wall/floor
					40	bag O; floor crack
					160	bag P; floor crack
					290	bag Q; floor crack
					40	bag R; floor crack

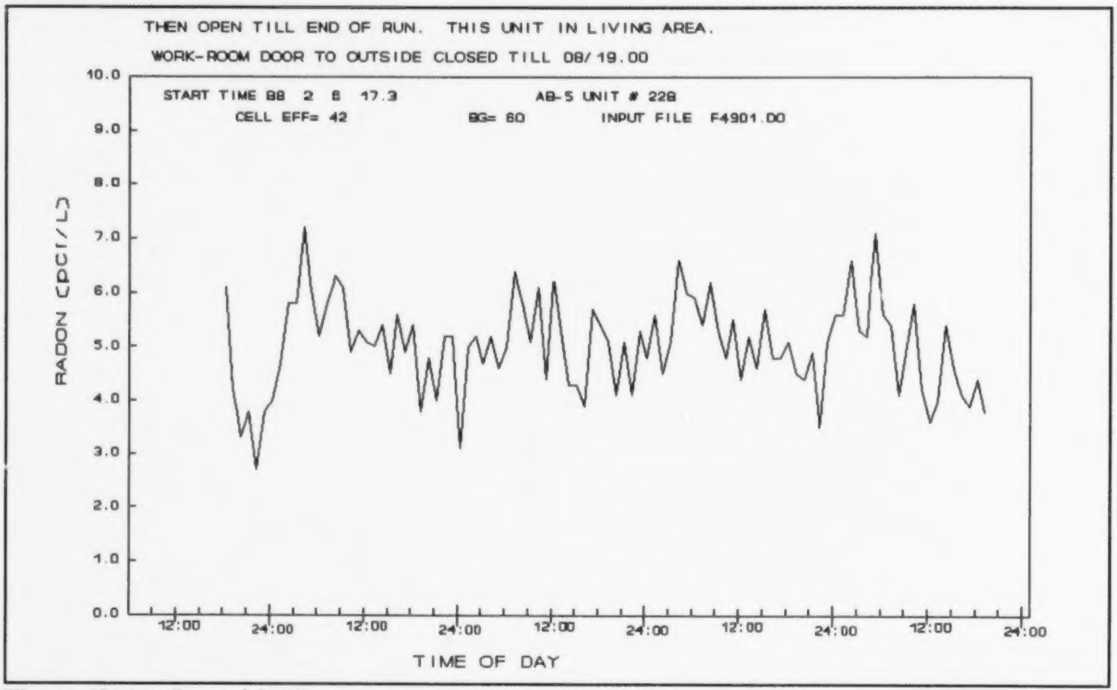


Figure 49-1. Pre-mitigation measurements in living room

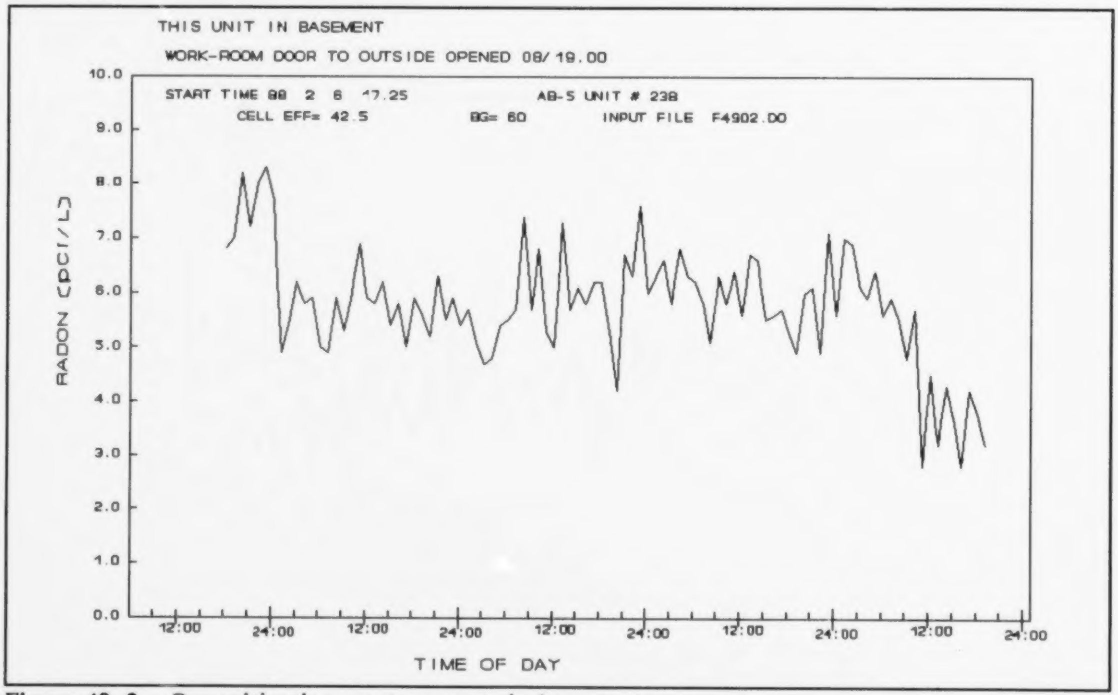


Figure 49-2. Pre-mitigation measurements in basement

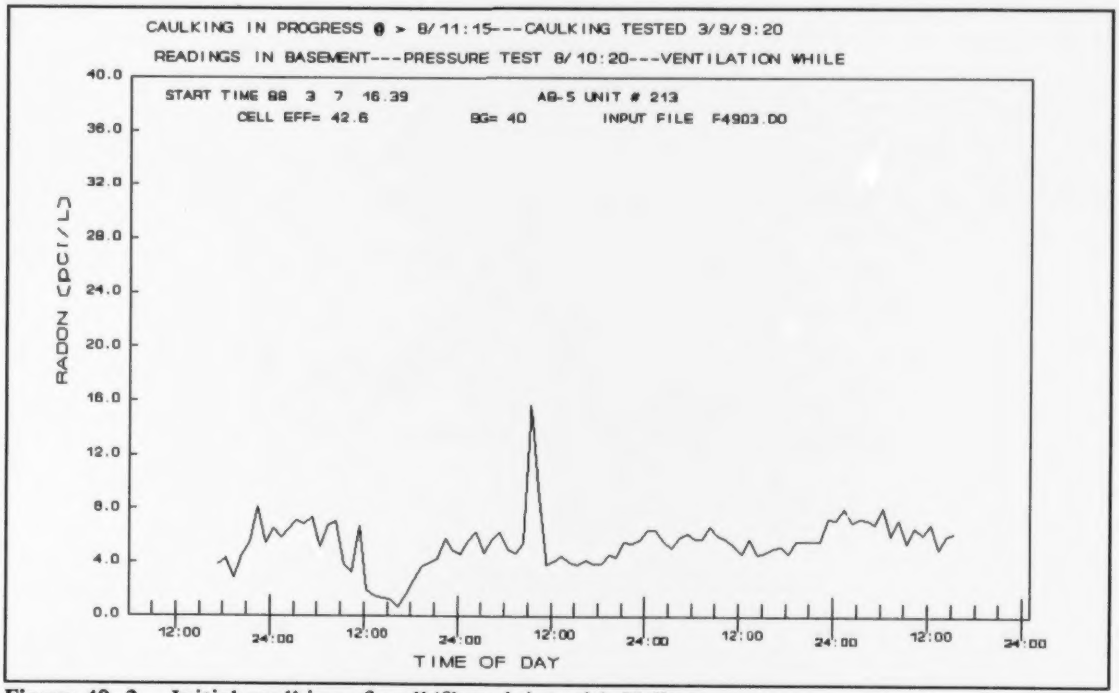


Figure 49-3. Initial caulking of wall/floor joint with Vulkem

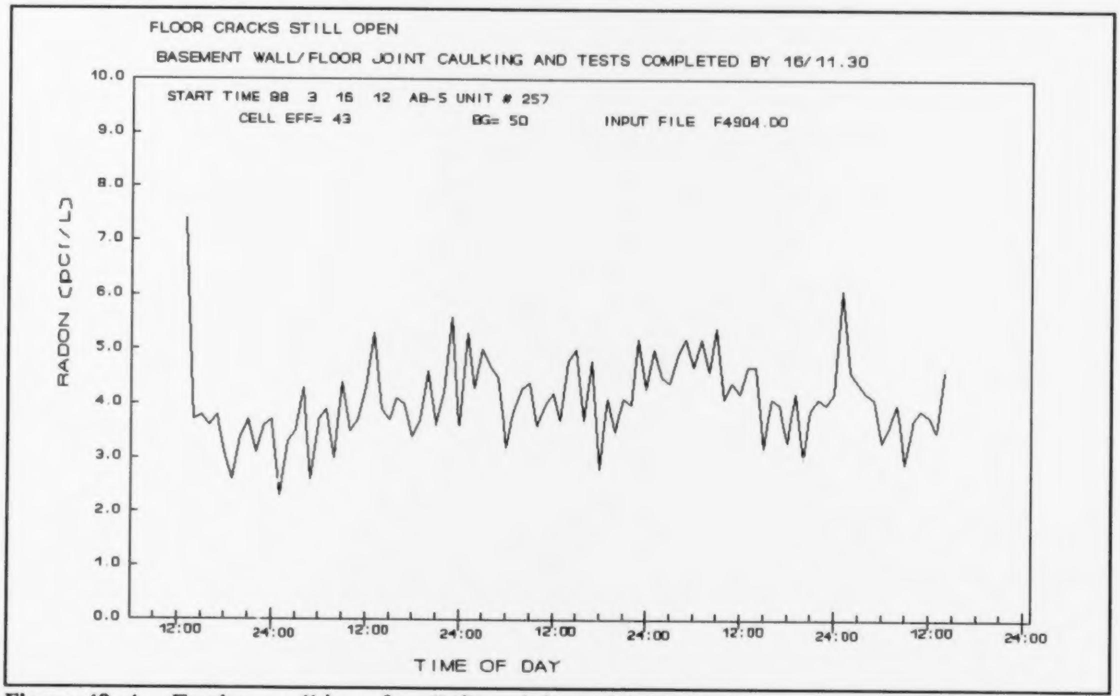


Figure 49-4. Further caulking of wall/floor joint, with Dymonic

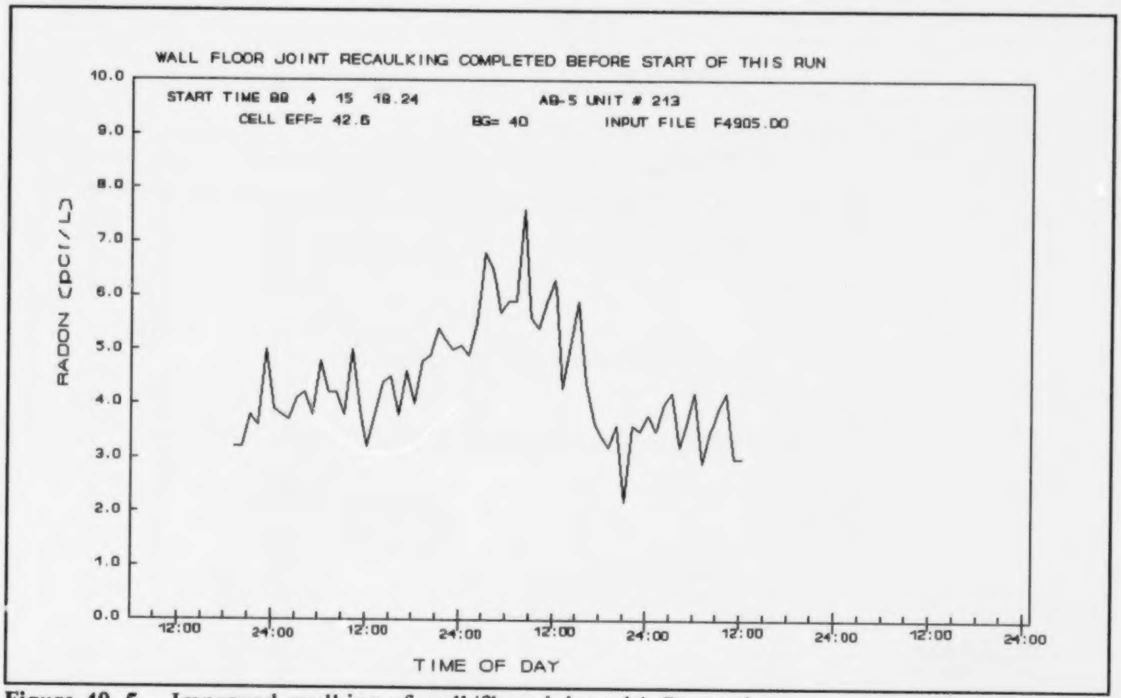
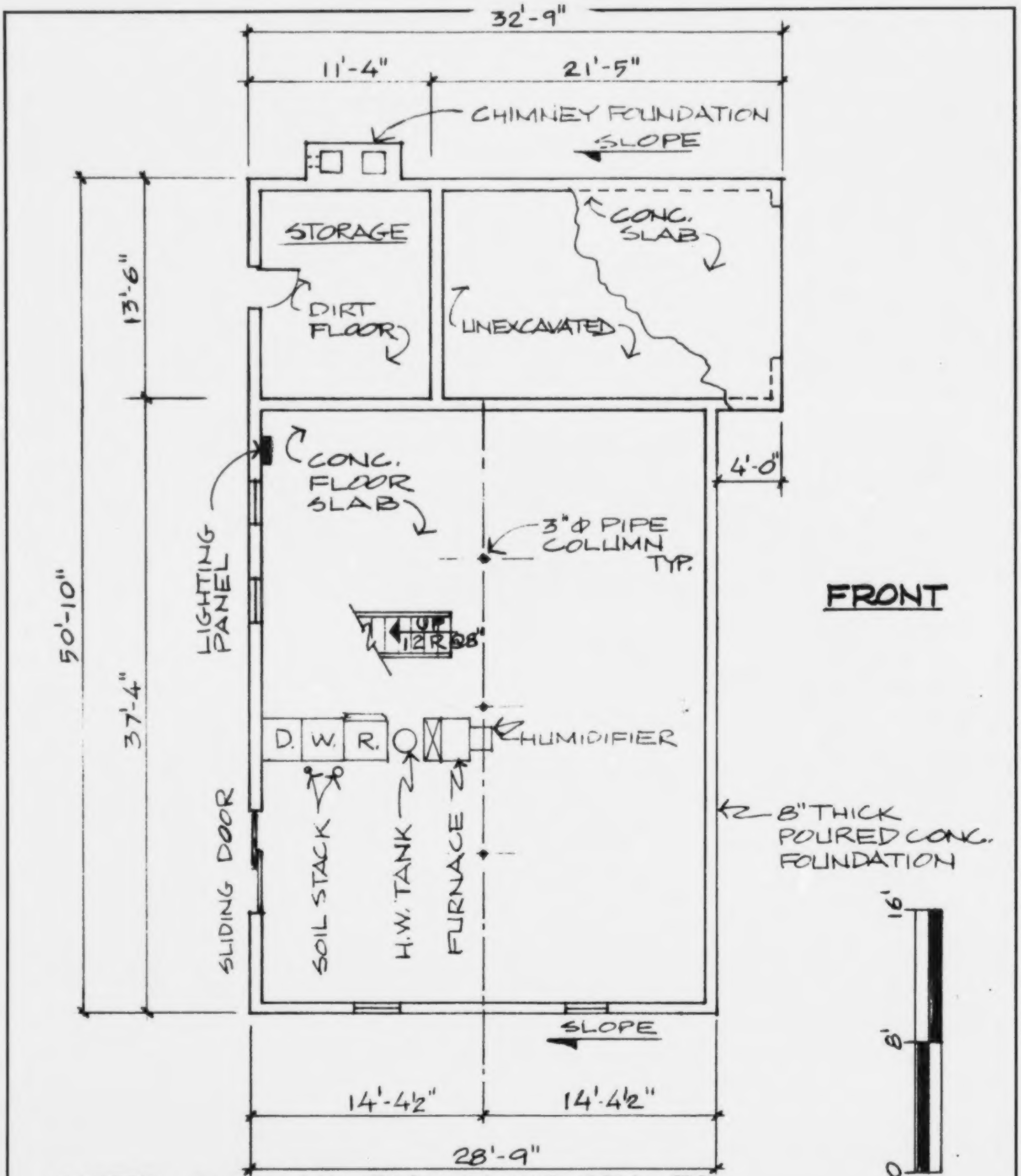


Figure 49-5. Improved caulking of wall/floor joint with Dymonic



NOTE: SLAB JOINTS & CRACKS SEALED

ACRES
Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON

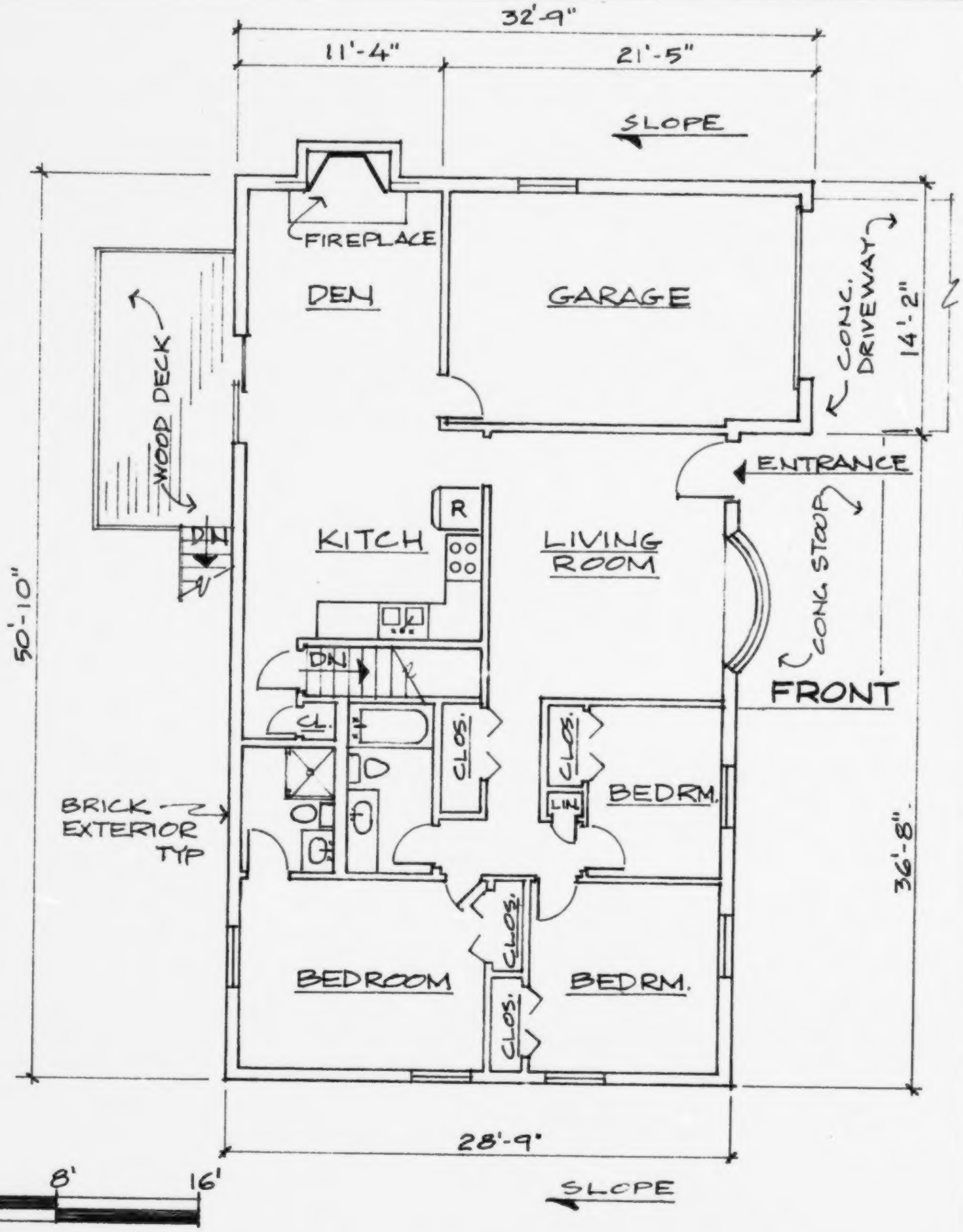
HOUSE NUMBER 49

BASEMENT/FOUNDATION PLAN

Date: MAY 1988

Mitigation system: JOINT SEALING

PHASE: FINAL



ACRES
Acres International Corporation

LOW COST REDUCTION OF INDOOR RADON

GRADE LEVEL PLAN

Date: 2/23/88

House Group: FULL BASEMENT

PHASE:

HOUSE NUMBER

49

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APPENDIX D

PROJECT SCHEDULE AND ACTIVITIES

D.1 OCTOBER - NOVEMBER 1987

D1.1 Preliminary Activity

An initial project meeting between the EPA and the Contractor's project management staff was held at the Research Triangle Park office on October 29, 1987, after a joint agreement had been signed between the EPA, Ohio Department of Health, and Dayton Regional Air Pollution Control Agency (RAPCA). The project goals, testing and selection procedures to be used, and the information available on the Dayton area was discussed. As the heating season was about to start in Ohio, it was agreed that long-term pre-mitigation radon measurements would be started in the houses as soon as thy were selected. Alpha-Track detectors for 30 houses were ordered. The preliminary field work for the project started with a 'Kick-off' meeting in Dayton, Ohio on November 4, 1987, between members of the EPA Research Triangle Park, and Region V, Ohio Department of Health, RAPCA, and the contractor. The goals and organization of the program were discussed, and the criteria for selecting houses from the WHIO-TV/RAPCA data base were agreed upon.

The initial selection of 105 potential candidate houses took place the following week, and the detector numbers were forwarded to Air Chek on November 10, 1987. Replies were forwarded by Air Chek to the contractor as they arrived, and were in turn forwarded to RAPCA in Dayton.

D.2 DECEMBER 1987

D2.1 Screening Visits

The Dayton RAPCA had a list of the 50 candidates by December 1, 1987. They contacted the home owners, and arranged for screening visits in during the week of December 7-11.Each house was visited by a team consisting of at least the EPA project manager, both contractor project managers, and a RAPCA representative. The RAPCA member and the EPA project manager introduced the team, and then explained the scope and goals of the program to the home owner. The contractor's staff inspected the exterior and interior of the premises, including crawlspaces, filled in a summary form prepared by the EPA for this inspection, photographed any items of interest, and finally interviewed the home owner on any unresolved building details. On December 8, a team from WHIO-TV met the group at one house and with the home owners consent, taped the inspection procedure and interviewed the home owner.

A preliminary selection was made at the end of each day, and a final field selection meeting was held on Saturday, December 12. Houses were divided into categories by construction type, and a short-list made up. The number of houses included in the short-list (29) was larger than needed for the program on the basis that if some of the houses were found unsuitable by later testing, there would still be sufficient houses to carry out the program.

D2.2 Initial Evaluation

The short-list showed that some modification would have to be made to the planned program, for there were very few houses without sumps but with poured concrete basement walls that would be suitable for a test of caulking alone as a mitigative measure. Most of these houses had extensive cracking of the basement walls and floor, which made them unattractive candidates, and many of the basements were at least partly finished. A new category was added — basement houses with slab-on-grade and a sump, for several of the basement houses visited were actually this type of house. The anticipated selection at this time was 20 houses, 4 crawlspace houses and 16 where some form of soil-ventilation would be the mitigation method.

The visits found that many of the WHIO survey detectors had been placed near sumps or in crawlspaces to maximize the reading, and probably did not represent the radon exposure of the occupants. As there were sufficient Alpha-Track detectors available, it was decided not to wait for house selection to be completed, but to start long-term radon measurements in all the short-list houses. The final selection procedure would also include a short-term continuous radon monitor survey. Over the next week, the short-list was reduced to 25 houses by one home owner dropping out, and rejection of two more sites after further analysis of the data collected. Alpha-Track detectors were placed in these 25 houses on December 17-18.

D2.3 Accommodation

A search was made for potential site accommodations on December 12/13. The most desirable area was felt to be to the east of Dayton, close to I-675. This highway connects to I-70 and I-75, and provided ready access to all the areas where houses were under consideration. A number of areas with rental accommodation were visited, and Fairborn seemed to be the best choice. Since the city includes Wright-Paterson Air Force base and Wright State University, there are a number of apartment buildings. Not all were suitable. Arrangements were made on Saturday 19 December to rent three apartments from January 1, 1988 in Fairborn near I-675.

D.3 JANUARY 1988

D3.1 Site Set-up

The site equipment was stored in ACRES main office in Buffalo, NY. This was moved to Dayton by a rented van, starting January 4, 1988. The route taken was along the south shore of Lake Erie, and the trip was delayed by a lake-effect storm which caused 28 tractor-trailers to come off the road in a 60 km stretch. A further delay was caused the following morning when the van would not start. The local rental agency provided assistance, and got it started by 11.00 h. Dayton was reached on the afternoon of January 6. When the Interstate exit was reached, it was found that the van accelerator was stuck in the fully open position. Fortunately, the brakes were in good condition, and the apartment complex was reached safely. Van unloading started that day, and was completed on January 8. The local rental agency towed the van away that day.

Equipment checks were started on January 8, as the radiation measurement equipment was needed for the EPA evaluation visits the following week. The weather had been very cold, and the van was unheated, and so the equipment required several hours just to reach room temperature. The internal batteries in one of the AB-5 monitors would not recharge, but the rest of the equipment was in working order.

D3.2 Evaluation Visits

Members of the EPA House Evaluation Team arrived on January 10, 11. They brought another AB-5 monitor, but that was not in working order when it arrived. Over the period January 11 - 14, a combined EPA/RAPCA/contractor team investigated sub-slab communication in 11 basement houses by pressure gradient measurements, plus freon travel time tests where appropriate.

D3.3 Evaluation Monitoring

One AB-5 monitor was used as a 'sniffer', to make measurements on the spot in the houses visited, but the other operational units were left in the first 4 houses visited. After the visits were over, these monitors were retrieved, and the 5 operational AB-5's used to make short-term measurements in a further 18 of the candidate houses. This was completed by January 24, and the information sent to the EPA to enable a final selection to be made between the sites. The RAPCA group assisted by making continuous radon measurements at 3 houses over the weekend and at the start of the following week. These houses had not been measured as the occupant of one had been on vacation, the AB-5 monitor battery had failed at a second, and there was not a monitor available to test the third. The results were forwarded to the EPA as soon as they were received.

Measurements in crawlspace houses were made in both the living area and the crawlspace. There were no power outlets in the crawlspaces, and so the AB-5's had to run on their internal batteries. The temperature in the crawlspace was only a few degrees C, and the battery life of the units was reduced to 18 - 24 hours.

D3.4 Selection

The selection process was completed by January 29, 1988. The EPA Project Officer telephoned the site and listed the houses selected. A formal notification was sent to RAPCA by letter on February 1, requesting them to inform all the candidate home owners of the decision that had been made regarding their house.

D3.5 Administrative

The project Health and Safety Plan was issued on February 22. A preliminary project file index was issued February 27. A date for an EPA Audit was tentatively set for March 1988.

D.4 FEBRUARY 1988

D4.1 Planning

A Proposed Mitigation Program was prepared for all houses during the first week. The plan was to proceed immediately to install sub-slab or sump ventilation systems in those basement houses selected for that treatment. While that work was in progress, tests would be carried out in the slab-on-grade houses to help design the systems intended for these houses, and electrical outlets would be installed in crawlspaces so that AB-5 monitoring could be carried out, and electrical heaters could be installed on services to prevent freezing during tests of increased ventilation rate. This plan was discussed and generally approved at a review meeting at RTP on February 11.

D4.2 Construction Program

An initial project schedule was produced, with field construction to start on February 23, and to continue till April 14. This was conditional on identification of a suitable contractor, availability of labor, and the owners signing an agrement to allow access to their houses.

A number of local contractors were visited during the first week, three of which seemed suitable, and were invited to bid to supply labor. One contractor built new homes, one was a small general contractor who did home improvements and renovations, and the third was a medium size contractor who specialized in renovation work. The third contractor (Staffco Construction of Fairborn) was the one finally selected. A purchase order for their services was issued on February 15, and accepted by them on the 25th.

The Access Agrement that had been prepared for the home owner to sign was unsatisfactory, and a new version had to be produced. As a result of this delay, the start of the construction program was rescheduled to February 29, with expected end at April 21.

An ACRES architect came to site February 21 - 27 to prepare standardized house plans. This was done for all houses except house 22, where the owners were on vacation.

D4.3 Investigation Program

Short-term premitigation measurements were started in the basement houses, and a measurement program was started in the slab-on-grade houses to see what effect the operation of the sub-slab heat distribution system had on the radon concentrations. Large changes in radon concentration from day to day were noted in several houses, which suggested that the planned measurement procedure of 2 days before and two days after any experimental change might not be long enough to give realistic evaluation of the effect of the change. The standard short-term monitoring period was increased to 4 days of measurements before and after any change.

The computer program that drove the plotter was modified to maintain accuracy over the large changes in radon concentration. The computer program that calculates radon concentrations from the AB-5 counts was modified to give the integral of radon exposure to the end of each hour to assist in evaluating the mean concentration when there were major changes in concentration.

RAPCA has a continuously updated data-base of wind and weather information. They agreed to provide a daily weather synopsis on a monthly basis.

D4.4 Administrative

A project review meeting was held at Research Triangle Park on February 11 to discuss the information provided by the investigation work, and to review the planned mitigation activities.

An Access Agrement had been produced for the project based on an agreement form that had been used at other EPA projects. This was an agreement by the home owner to allow access to their property for measurements and installation of mitigative equipment. The form of agreement was not satisfactory to two of the first three home owners to which it was presented. A detailed review at site showed that major changes were needed to make it express clearly the aims of the agrement and the work to be carried out under the program. Among other omissions, the initial version did not say that the program would be carried out at no charge to the home-owner, nor that any damage caused to the property during the installation would be repaired. A draft revised agrement was produced by February 15, and all parties gave it priority in review. A revised and agreed version was received at site on February 19. This version was distributed to all home owners, either during a visit, or by mail, and a sufficient number were returned by February 29 to start the construction program.

D.5 MARCH 1988

D5.1 Construction Program — Materials

The preferred piping material for the soil ventilation systems is light weight plastic pipe (drain pipe). It is lighter, cheaper, and easier to work with than the standard sewer piping. Local supplies of the pipe were good, but few places carried more than a few fittings. Only one supplier, in Springfield, had a good supply. The local pipe comes in two colors, white and cream, and the fittings in cream, tan and two shades of white. A six-to-four inch reducer had been used at other locations to connect the fan to the piping. No such reducers were available locally, and a supply was finally obtained by special order.

There were several local suppliers of caulks and sealants, but the materials required for the testing were not in stock, and had to be ordered from the factory. Delivery was slow and erratic.

Four "radon mitigation" ventilated sump covers were ordered from a commercial supplier. The units came in two parts, and were to be joined by a screwed and gasketed joint, and braced by gluing in a bar. There was an opening for a four inch exhaust pipe, but the openings for the sump-pump power cord and the discharge line were to be jig-sawed. There was no opening for a drain, and the unit was convex to the floor by 50 mm. Most houses with a sump use the sump as a floor drain, and so a satisfactory cover should include a drain. The covers were regarded as unsuitable for use, and the decision was made to fabricate any covers needed out of Lucite.

Two types of fan were ordered for the program. One was an in-line centrifugal fan with a plastic body and nominal 150 mm diameter inlet and outlet connectors. This fan was to be used for all initial experimental work, for it could be physically reversed in its mounting in a minute or so. The second fan was a roof mounted centrifugal fan with a plastic body and a nominal 100 mm inlet bell. This fan was to be used for permanent installations. The plastic body was so flexible that great care had to be taken in mounting, or else the fan wheel fouled the body.

A hand-held power auger with a 3 section auger 2.7 m long and 75 mm in diameter was ordered to investigate the soil around and beneath the houses. The auger was delivered in several packages spread out over several days, and one auger flight was incorrect and had to be replaced. The identification on the package was right, but the wrong unit was in the package.

D5.2 Construction Program — Field Work

Temporary sub-slab ventilation systems were installed in 7 basement houses, and in 4 slab-on-grade houses. The wall/floor joint was caulked closed in 2 houses. The vents in the 4 crawlspace houses were all made operable, and temporary electrical hook-ups and temporary crawlspace ventilation systems were fabricated for each house. Augering was carried out at 4 houses.

D5.3 Investigation Program

Tests of sub-slab permeability and connectivity were carried out in the slab-on-grade houses. The permeability was generally good, but the connectivity was poor. The expected performance of any sub-slab ventilation system installed in these places was expected to be poor, for there was every reason to believe that the depressurization would be confined entirely one segment of the sub-floor space. However, performance of soil ventilation systems installed in the houses was much higher than expected. Good performance was achieved by all the soil ventilation systems installed this month.

D5.4 Administration

The field office was often unoccupied during the day, and so RAPCA provided considerable assistance by acting as the receiving agent for equipment and materials.

D.6 APRIL 1988

D6.1 Construction Program — Field Work

The temporary mitigation systems in the basement houses were all converted to permanent installations during the month.

D6.2 Investigation Program

The measurement program was completed this month. Post-mitigation testing of the final system was completed in all houses with soil ventilation systems. All systems were satisfactory. At those houses where the performance was good at lower fan speeds, the speed was adjusted so that the system operated at lower noise.

Temporary sub-slab ventilation systems were tested in the slab-on-grade houses, with good results. Installation of permanent systems was planned for May.

Temporary ventilation systems were tested in the crawl space houses with simultaneous radon and ventilation rate measurements. The most effective system found was forced exhaust of the crawlspace.

D6.3 Administration

A joint EPA Region IV — States meeting was held 12th to 14th April in Dayton. As part of the program, participants visited a number of houses where construction work (mainly replacement of temporary to permanent systems) was in progress.

The owners of house 31 were transferred to another city, and put the house up for sale. They requested that only test work be done, so plans for a permanent installation were deferred until the house was sold and an agreement could be signed with the new owner.

The field program was almost complete by the end of the month. A small storage unit was rented to store construction equipment and materials until the resumption of work in the fall.

D6.4 Audit

An audit of field operations and record keeping was conducted by the ACRES Quality Assurance Supervisor on the 18th April.

D.7 MAY 1988

D7.1 Construction Program

A small construction program was started on 28th to complete the program. Permanent sub-slab systems were installed in the 3 slab-on-grade houses left in the program, but they were not operational at month end as the electrician was not able to schedule the visits to connect them. and a permanent sump ventilation was placed in house 32, where the sump had been sealed as part of the sealant test program. Ventilation fans with speed controls were installed in the crawlspaces of the crawlspace houses. Auger tests were carried out at the last three crawlspace houses.

D7.2 Measurement Program

Alpha-Track detectors were installed during the first week of May in all 16 demonstration homes. This is the first of four quarterly detector sets to measure the average radon exposure of the occupants over a year.

D7.3 Administration

Staff accommodation on site was given up effective the end of the month. The field office was retained.

D.8 JUNE 1988

D8.1 Construction Program

The small construction program was completed in May, but the fans at the slab-on-grade houses were not operational since an external power line had yet to be run to the fans. The electrician installed these lines during the month. This completed all scheduled construction work.

D8.2 Administration

The project was placed on a stand-by status as all scheduled field tasks had been completed.